Cultivating Diversity

The Expert Panel on Plant Health Risks in Canada

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THE COUNCIL OF CANADIAN ACADEMIES
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This project was undertaken with the approval of the Board of Directors of the Council of Canadian Academies (CCA). Board members are drawn from the Royal Society of Canada (RSC), the Canadian Academy of Engineering (CAE), and the Canadian Academy of Health Sciences (CAHS), as well as from the general public. The members of the expert panel responsible for this report were selected by the CCA for their special competencies and with regard for appropriate balance.

This report was prepared for the Government of Canada in response to a request from the Canadian Food Inspection Agency (CFIA). Any opinions, findings, or conclusions expressed in this publication are those of the authors, the Expert Panel on Plant Health Risks in Canada, and do not necessarily represent the views of their organizations of affiliation or employment, or the sponsoring organization, the CFIA.

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The Expert Panel on Plant Health Risks in Canada would like to acknowledge the First Nations, Inuit, and Métis Peoples who have lived in partnership with plant life on the lands now known as Canada. For generations, plants have been integral to Indigenous ways of life, providing food and medicine, and acting as cornerstones of culture, tradition, and spirituality.

This report was completed on the ancestral, unceded, and ceded territories of many different Indigenous nations, where people live in reciprocal relationships with plants and have done so for millennia. The Council of Canadian Academies (CCA) acknowledges that our Ottawa offices are located in the unceded, unsurrendered ancestral home of the Anishinaabe Algonquin Nation, who have nurtured the land, water, and air of this territory for millennia and continue to do so today.

Though our offices are in one place, our work to support evidence-informed decision-making has broad potential impact across Canada that may contribute to collective actions to address plant health risks in ways that empower Indigenous decision-making and ethically include Indigenous knowledge systems.

We at the CCA recognize the importance of drawing on a wide range of knowledges and experiences to inform policies that will build a stronger and more equitable and just society.

The Council of Canadian Academies

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The CCA is supported by its three founding Academies:

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The CAE is the national institution through which Canada's most distinguished and experienced engineers provide strategic advice on matters of critical importance to Canada. The Academy is an independent, self-governing, and non-profit organization established in 1987. Fellows are nominated and elected by their peers in recognition of their distinguished achievements and career-long service to the engineering profession. Fellows of the Academy are committed to ensuring that Canada's engineering expertise is applied to the benefit of all Canadians.

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The CAHS recognizes excellence in the health sciences by appointing Fellows based on their outstanding achievements in the academic health sciences in Canada and on their willingness to serve the Canadian public. The Academy provides timely, informed, and unbiased assessments of issues affecting the health of Canadians and recommends strategic, actionable solutions. Founded in 2004, the CAHS appoints new Fellows on an annual basis. The organization is managed by a voluntary Board of Directors and a Board Executive.

Expert Panel on Plant Health Risks in Canada

Under the guidance of its Scientific Advisory Committee, Board of Directors, and founding Academies, the CCA assembled the **Expert Panel on Plant Health Risks in Canada** to undertake this project. Each expert was selected for their knowledge, experience, and demonstrated leadership in fields relevant to this project.

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Danielle Way, Associate Professor, Department of Biology, Western University (London, ON)

Message from the President and CEO

We may notice the abundant trees, shrubs, grasses, and crops that dot the Canadian landscape, but how much do we appreciate how critical plants are to our daily lives — from the food we eat, to the air we breathe, to the medicines we take? Plants are indispensable to our economic and social well-being, with the agriculture and forestry sectors being key employers in many rural, remote, and Indigenous communities.

Despite their abundance, plants face many threats, such as rising temperatures, changing precipitation patterns, extreme weather events, disease, and new predators. In the summer of 2021, we witnessed the devastating effects of drought and record high temperatures across Canada and in many parts of the world, where forests burned extensively. These events serve as a reminder that risks to plant health can impact our economy, food production, forestry activities, air quality, and even homes and businesses.

Canada's vast and diverse geography, its involvement in international trade systems, its variety of management approaches, and its shared responsibilities among various orders of government and other actors all complicate our ability to address plant health risks. Recognizing the essential role plants play in our lives, the Canadian Food Inspection Agency asked the CCA to examine the most significant current and emerging risks to plant health in Canada. Panel members brought expertise in agriculture and crop science, forestry, economics and trade, climate change, policy and regulation relating to plants, and the social impacts of plant health risks and mitigation strategies. *Cultivating Diversity* details the many existing and emerging risks to plant health and offers insights into promising practices that may help to mitigate them.

I extend my thanks to Panel Chair Deborah Buszard and to every member of the expert panel for their many months of work on this report — all of it undertaken virtually during COVID-19. They signed on to this process at an uncertain time, and their flexibility and patience were admirable. Over the course of the assessment, key guidance and oversight were provided by the CCA's Board of Directors, Scientific Advisory Committee, and founding Academies: the Royal Society of Canada, the Canadian Academy of Engineering, and the Canadian Academy of Health Sciences. I offer my thanks to them all.

Eric M. Meslin, PhD, FRSC, FCAHS

President and CEO, Council of Canadian Academies

Message from the Chair

Plants have sustained life on this planet for millennia, providing food, shelter, and clean air. Further, plants are fundamental to human society, providing economic, cultural, medicinal, recreational, and aesthetic services we all enjoy. They are, in every way, vital to our collective survival. But increasingly the plants we depend on face serious threats to their health and well-being, with potentially devastating environmental, economic, and social consequences.

Changes to the environment and to land use, as well as the introduction of new pests, are putting increased pressure on plants. While these challenges are not new, they are exacerbated by climate change, the globalization of trade and movement of people, and issues of governance in a complex pan-Canadian and international plant health system. There is a great deal we don't know about how these stressors will affect plants and interactions among plants, pests, and their environment. We do know, however, that unless these changes are effectively managed, they could upend the stable ecosystems and environments that plants underpin, affecting climate, human and animal health, biodiversity, and food security.

While this report focuses on plants primarily managed for economic returns — agricultural crops and forests — the Panel recognizes the importance of safeguarding plant health in all ecosystems. To this end, it found that an approach to plant health that prioritizes both economic and ecological values has the potential to increase the resilience of plants, support biodiversity and land conservation, and contribute to climate change mitigation. Further, meaningful engagement with Indigenous Peoples is critical to ensuring their future and the future health and sustainability of the diverse ecosystems in Canada. Including Indigenous knowledge can provide opportunities for collaboration and learning in areas such as policy design, monitoring, and identification and management of risks.

Technological innovations can also help address many risks to plant health. For instance, remote sensing and precision agriculture and forestry are being effectively applied in land-use management and may help mitigate the impact of climate change and pest outbreaks, while plant breeding allows development of crop varieties better adapted to existing and emerging risks. It is vital that Canada continue to support the high-quality research and development essential to ensure the future health, sustainability, and global competitiveness of its agriculture and forestry sectors. As the challenges facing plants rapidly evolve, so too must our approaches to protecting their health if we want to preserve the wealth and sustenance they continue to provide us.

I’d like to thank the members of the Panel who all generously lent their time and expertise to this project over the past year, and particularly for their sustained engagement over the course of the COVID-19 pandemic, wherein our work was completed entirely through a virtual format. I would also like to thank the CCA staff for their excellent research, guidance, support, and responsiveness throughout this process. This project was also shaped by the peer reviewers and experts who volunteered their time to review and provide input respectively, and the Indigenous scholars who generously shared their knowledge with us. On behalf of the Panel, I’d like to thank everyone involved in the development of this report.

Deborah Buszard, PhD

Chair, Expert Panel on Plant Health Risks in Canada

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Peer Review

This report was reviewed in draft form by the individuals listed below — a group of reviewers selected by the CCA for their diverse perspectives and areas of expertise.

The reviewers assessed the objectivity and quality of the report. Their confidential submissions were considered in full by the Panel, and many of their suggestions were incorporated into the report. They were not asked to endorse the conclusions, nor did they see the final draft of the report before its release. Responsibility for the final content of this report rests entirely with the authoring Panel and the CCA.

The CCA wishes to thank the following experts for their review of this report:

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The peer review process was monitored on behalf of the CCA's Board of Directors and Scientific Advisory Committee by **John P. Smol, PhD, O.C., FRSC, FRS,** Canada Research Chair in Environmental Change and Distinguished University Professor, Biology Department, Queen's University. The role of the peer review monitor is to ensure that the Panel gives full and fair consideration to the submissions of the peer reviewers. The Board of the CCA authorizes public release of an expert panel report only after the peer review monitor confirms that the CCA's peer review requirements have been satisfied. The CCA thanks Dr. Smol for his diligent contribution as peer review monitor.

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Barry Gibbs, Executive Director, Canadian Council on Invasive Species

Brent Larson, Implementation Facilitation Unit Lead, International Plant Protection Convention

Henry Lickers, Canadian Commissioner, International Joint Commission

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Executive Summary

Plants are integral to the environment and the well-being of people in Canada. They are a substantial part of, and provide habitat for, the diversity of life; make up the food we eat; are used for medicines, fibre, and timber; help regenerate soil, filter water, and fix carbon; and supply the oxygen we breathe. Plants underpin the fundamental relationships humans have with the land and define the diverse landscapes we live in. They are also vital to the Canadian economy — the primary agriculture and forestry sectors employ nearly half a million people, contribute nearly 3% of Canada's overall GDP, and are the main sources of economic well-being for many communities. Recognizing the importance and essential role of plants in maintaining a variety of economic and social goods — from food security to environmental sustainability to public health — the Canadian Food Inspection Agency (CFIA) asked the Council of Canadian Academies (CCA) to answer the following question:

What are the most significant current and emerging risks to plant health in Canada?

The CCA assembled a multidisciplinary panel of 14 experts (the Expert Panel on Plant Health Risks in Canada, hereafter the Panel). Panel members brought knowledge and experience from agricultural and horticultural sciences, forestry, economics and trade, climate change, policy and regulation relating to plants, and the social impacts of plant health risks and mitigation strategies. While the primary focus of the Panel's assessment was on plants of economic importance (i.e., agriculture and forestry), this report also addresses risks to plants in other ecosystems across Canada.

Main Findings

The Panel defined *plant health* as the ability of plants to maintain their ecosystem functions, including provisioning (e.g., food, wood, fibre), regulating (e.g., water and air quality), supporting (e.g., nutrient cycling, soil formation), and cultural (e.g., recreation, education, spiritual) functions. Risks to plant health have the potential to negatively impact the ecosystem functions of any plant, and can arise from any organism, system, or process. These risks can vary in potential scope and severity across the geography of Canada, as well as through time and in the judgment of different actors, sectors, and communities. Thus, the Panel found no single answer to the characterization or prioritization of current and emerging risks to plant health in Canada, nor on the appropriateness of specific mitigation measures for any one risk. Indeed, there is a diversity of actors in the plant health system, some of whom may hold differing or divergent perspectives, reflecting local contexts and concerns (e.g., crop types, farm sizes, forestry practices, management strategies). However, the Panel agreed on the types of risks that can impact plant health, the characteristics of plants and plant systems that are vulnerable to risks, and commonalities among strategies to support resilience — that is, the ability to maintain or recover ecosystem function during or following an adverse event.

The Panel identified three main categories of risks to plant health:

Changes to the environment, including higher temperatures, extreme weather events, changing precipitation levels, and land-use changes;

Pests, including predators (e.g., insects), competitors (i.e., weeds), and disease (i.e., pathogens);

Issues of governance, including failures in surveillance, communication, and coordination among relevant actors in the plant health system.

Key exacerbating factors — climate change, the movement of people and goods, and evolutionary processes — can increase the likelihood of adverse events, the rapidity of changes, and the severity of potential impacts to plant health. These exacerbating factors can act directly on pests, plants, and the environment, but also indirectly by altering plant-pest-environment relationships. Moreover, interactions among exacerbating factors (e.g., environmental changes that favour the establishment of novel pests) can accelerate and amplify adverse events in unanticipated ways, making the assessment and management of plant health risks more complex and uncertain.

The rapid pace of environmental change challenges the ability of plant populations, as well as the ability of the plant health system, to adapt

Plants need a suitable climate and adequate moisture to grow optimally. While changes to these abiotic (i.e., non-living) components occur naturally, climate change (including higher temperatures and more frequent and severe extreme weather events such as droughts, storms, and wildfires) is intensifying these variations and making them more difficult to predict and mitigate. Environmental threats to plant health are interconnected and can have cumulative and interrelated effects. Climate change — coupled with land conversion (e.g., for agriculture, forestry, or urbanization) and changes in pest distributions — is altering the quality, availability, and connectivity of plant habitats, resulting in native biodiversity declines. These environmental risks also cause substantial plant mortality and damage, leading to changes in the quantity and quality of natural ecosystems, agricultural crops, and timber supply in Canada. Soil health and pollination services — which are essential for plant health — are also impacted by land-use changes, climate change, and pests.

As habitats change, plant populations must shift their distributions, adapt to changing conditions, or face extirpation. However, they may not be able to adapt fast enough to grow optimally, or even survive, under the increased rate and unpredictable nature of changing climatic conditions and pest populations coupled with factors such as urbanization. Similarly, the plant health system itself — those institutions and people charged with protecting plant health in Canada — will need to address threats that are less predictable in their timing and more uncertain in their scope. Efforts by actors within the Canadian plant health system have focused on innovation and technology that have mitigated some of the ongoing and emerging risks; however, the scale, severity, and frequency of future environmental changes will be a constant challenge. A continuous risk management approach — iterative and adaptive processes centred on ongoing communication and documentation — is a promising practice for plant health managers seeking to address risk in a dynamic landscape.

There is a need for the assessment of appropriate and relevant indicators and metrics across all aspects of the plant health system

The successful adaptation of plant health management to environmental changes creates an increased demand for information, including indicators of change. While there is an overall gap in accessible metrics, and no systematic tracking of plant health-related indicators, those related to drought, fire weather, fire regimes, growing season length, plant mortality, pests, and species distribution (among others) are relatively well documented, as are broad-scale financial metrics, such as data on exports, GDP, and crop production values. However, there is currently limited capacity to document additional indicators such as extreme weather events, plant regeneration, biodiversity, and phenology (i.e., biological life-cycles, such as flowering or fruiting seasons). The development of new methodologies, including technological and practical innovations as well as advances in statistical methods, offers an opportunity to review the availability, applicability, and potential overlaps of indicators and metrics of plant and soil health across agriculture, forestry, and natural ecosystems. The Panel notes that the metrics chosen as indicators of plant health drive the types of management strategies employed (i.e., "what you measure is what you manage"); this suggests that a careful and deliberate consideration of plant health indicators and metrics is warranted to inform future policy decisions.

Ecosystems with fewer barriers to introduction and spread, that have more available habitat, and that have limited control options face greater threats from plant pests

The number and size of pest introductions increase with the movement of people and goods; however, climate change and land-use changes can also alter habitat quality and environmental conditions, resulting in degraded plant ecosystems that favour pest establishment.

Plant systems are more vulnerable to pests when the likelihood of their introduction is higher, when environmental conditions are suitable for their establishment (i.e., available habitat), and when few barriers exist to prevent their spread. Some pest species are native to Canada, while others are imported for agriculture or landscaping use, or unintentionally carried in soil, on wood pallets, or on other plant products. Other pests travel into Canada via wind, water, or animals. Strategies to lower the vulnerability of ecosystems to plant pests include improving detection and phytosanitary procedures, managing the environment to reduce suitability, and creating barriers to reproduction and spread, among others (Figure 1). Future ecosystem health will be affected by how well biosecurity regulations and enforcement limit new pest invasions. Effective regulation and enforcement require ongoing research and development to, for example, improve monitoring techniques and technologies, identify priority areas and target species, and improve mitigation strategies for established pests. Improving current forest and agricultural management practices depends on the continued growth of practical theory and knowledge on the determinants of pest abundance, as well as on how biotic and abiotic conditions affect plant and pest growth, reproduction, and species interactions.

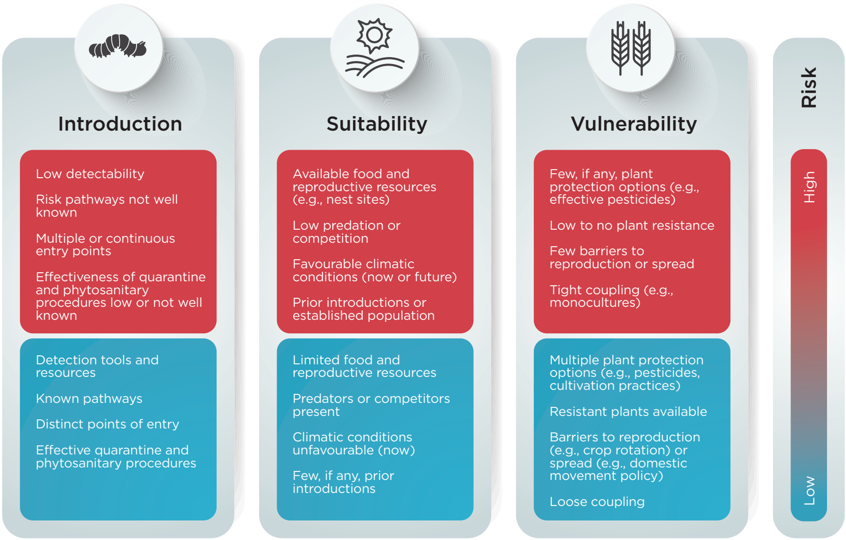


Figure 1 Factors Influencing Pest Risks to Plant Health

High-risk plant health scenarios involve pests that are largely undetectable (and uncontrolled) arriving via multiple pathways into areas with favourable environmental conditions (including ample food and reproductive resources), for which there are few, if any, protection or control options.

Supporting diversity in plant life and ecosystem functions, and in economic and management strategies, increases resilience

The adaptability and resilience of ecosystems are strongly linked to functional diversity. A natural ecosystem (e.g., a forest or a prairie) with high functional diversity may be better able to withstand a variety of disturbances, as it is composed of plant species with a wide range of response mechanisms to change. High functional redundancy also ensures the continuity of an ecosystem function if one species disappears. Management practices that support biodiversity and redundancy in ecosystem functions can increase resilience. For example, a shift in forest management practices that focuses on maintaining or increasing tree diversity, rather than maximizing growth of a few species of economic value, is arguably necessary to ensuring forests are resilient to global changes. Diverse options for pest management, such as different breeding technologies, cultivation practices, and chemical interventions, as well as diverse farm types, sizes, and compositions, encourage resilience in the agricultural system. For example, climate change can alter the competitiveness of pest species, and management practices themselves impose selection pressures on pest populations, shifting the relative effectiveness of tools and strategies over time. Different crop varieties, selected for specific traits that enable them to tolerate stressors, have been important for climate adaptation and pest management. Ongoing development of molecular tools that can improve breeding efficiency include research and development in genomic selection, genome editing, molecular markers, and epigenetics. While the Canadian regulatory system is generally well respected, reliably evidence-based, and considerate of safety standards, there is room for improvement in efficiency, consistency, and transparency in order to support growth and innovation in different areas, including the regulation of new products.

Fostering innovation in, and facilitating access to, new technology and practices will further support resilience, sustainability, and profitability for agricultural producers. However, the availability of different tools and practices alone is not sufficient to support farmers, who must also make decisions about the appropriate and timely use of these tools and practices that depend on factors such as local soils, weather forecasts, skills and capacity, and costs, among others. Moreover, technological advances are not the only solution to addressing plant health risks; research and development of locally adapted cropping strategies, including agroecological solutions such as intercropping, cover cropping, and extended crop rotations, are necessary to ensure a robust and diverse agricultural system.

Promising practices in plant risk management include better detection, identification, and modelling of pest populations and growing conditions to inform decisions

New and improving technologies to complement visual identification of pests in natural ecosystems, forestry, and agriculture include faster, highly sensitive, and more affordable DNA sampling techniques, field kits, and lab testing. Field surveys can be supplemented by additional detection and quantification tools, such as aerial drone surveys (to quantify damage) and volumetric spore traps (for fungal pathogens). Digital technologies are increasingly applied in plant health management. For example, precision agriculture is a crop management system based on data-driven analysis of spatial and temporal variability in crop and soil factors. It uses real-time, robust mapping of crop, soil, and environmental variables to assist management decisions. Crops are managed through metrics including yield prediction, pest detection, disease severity, crop quality, and species recognition. By providing accurate estimates of pest incidence and severity, as well as measuring the negative effects of pests on the quantity and quality of field crops, precision agriculture can create a basis for targeted interventions to address plant health risks. Ground-level climate vulnerability assessments, which assist in the identification of risks, can also help strengthen Canada's adaptation capacity across different ecosystem types.

Challenges to adopting and applying digital technologies to manage plant health risks include availability of expertise, issues of data governance, and cost

While there is ongoing research and technological development in agriculture, forestry, and conservation, it is not clear whether Canada's current education and training programs are adequate to fully take advantage of these improvements. In particular, the increasing volume and rapidity of data acquisition point to a need for specialists in data management and analysis among practitioners, industry, and regulators. Not all data are useful or meaningful, and such data can result in a glut of information with little relevance, inaccurate interpretations, or misuse. Thus, expertise in data management and analysis will be increasingly in demand by both industry and regulators, among others, as will the need for governance structures that ensure data can be effectively acquired, managed, accessed, interpreted, and used. The ongoing development of precision agriculture and forestry will require advanced skills in areas such as robotics, computer programming, software systems, and agronomy to design and operationalize new technologies. There will be an accompanying need to support and train practitioners as they more fully integrate digital technology into their operations. The cost of adoption is also of concern, particularly in forestry, as the industry is both cost-sensitive and often reactive, rather than proactive, regarding phytosanitary issues. The effective use of promising practices in local contexts can be facilitated through financial and community supports that help manage the economic risks of adopting different methods and accelerate learning.

Coordination among diverse actors is essential for the successful deployment of resources and knowledge to mitigate emerging risks to plant health

The governance of Canada's plant health system is informed by, and follows, international standards and agreements, including the World Trade Organization's (WTO) *Agreement on the Application of Sanitary and Phytosanitary Measures* (SPS Agreement), the *Convention on Biological Diversity* (CBD), and the *International Plant Protection Convention* (IPPC). Canada is a member of the North American Plant Protection Organization (NAPPO), which commits Canada, Mexico, and the United States to trilateral cooperation in preventing the spread of plant pests, and facilitates regional trade in plants and plant products. While the CFIA is the federal body tasked with protecting the plant resource base, the environment, and plant-related industries in Canada, issues related to plant health also fall within the mandates of several other federal agencies, as well as provincial and territorial governments. This may lead to duplication of efforts or a lack of clarity in the regulatory system from the perspective of practitioners, industry, and the public. Land and resource management also fall under treaty and Indigenous rights (including those defined in land claims and self-government agreements) and Indigenous Peoples' commitment to land stewardship. Thus, responsibility for protecting plant health in Canada is complex and dispersed across government agencies and jurisdictions, Indigenous communities, and other non-governmental actors.

The diversity of actors in the Canadian plant health system is a strength, as it helps to create a comprehensive approach and lessen system-wide gaps. However, the number of actors also presents challenges, such as legislated mandates that have competing or conflicting goals and priorities, which can lead to potential oversights, duplicate or overlapping efforts, and failures to coordinate and share information and research. Across Canada, plant health risks and their management differ among and within sectors. For example, agricultural land is primarily privately owned, whereas forestry often involves leases of publicly owned lands. This contrast leads to different management approaches and incentives that have different implications for plant health risk management. Efforts aimed at managing plant health risks vary across the country — some provinces and territories have more robust systems of risk surveillance, monitoring, and management than others. This unevenness creates gaps. Among the most significant risks identified in the plant health system are the information silos produced by different actors who fail to connect, or whose research remains unknown to each other without a shared information network. Cultural values, climate change impacts, and biodiversity priorities differ across the country, as do the livelihoods and worldviews that influence how people understand their relationships with plants and define plant health priorities and responsibilities.

Including Indigenous people in the plant health system is an opportunity for Canada to help mitigate risks, meet its obligations, and move towards reconciliation

There is a deep and longstanding relationship between Indigenous Peoples and plant life. Indigenous people in Canada and elsewhere recognize they are in reciprocal relationships with non-human beings, including plants, which create obligations of nurturing and co-habitation. In relation to plant health, Indigenous legal traditions can include prescribed practices of selective harvesting, pruning, soil aeration, and planting (among others) that demonstrate a respect for plants, which is reciprocated by future abundance. Indigenous knowledge includes long-term ecological and environmental data, which can provide insight into how ecosystems have changed over time. For example, mainstream environmental monitoring programs have increasingly sought to include Indigenous people, drawing on Indigenous knowledge to better understand ecosystems. However, in many of these instances, Indigenous people are treated as stakeholders who bring forward important knowledge, but who lack influence in decision-making.

Similarly, Indigenous people are often excluded from Canada's mainstream agricultural system, yet they are connected to agriculture through precolonial trade networks, agricultural provisions in the numbered treaties, and Indigenous-led farming and agricultural leasing on First Nations reserve lands. While there are instances of Indigenous management in forestry (e.g., through community forests), these are in the small minority of all operations. Indigenous communities, rights-holders, and experts have been long overlooked among policymakers, and there has been a lack of meaningful engagement with Indigenous people by the federal government departments responsible for managing plant health. Including Indigenous representation beyond consultation, as well as learning from and supporting Indigenous plant management practices, are important components of a robust and effective plant health system in Canada.

An inclusive, connected, and responsive plant health system is key to addressing current and emerging plant health risks in Canada

Inclusiveness depends on an approach that incorporates multiple ways of knowing, such as the natural and social sciences, economics, and Indigenous and practitioner knowledge. An inclusive approach also focuses on the management of plant health risks with an understanding of how risks are intertwined with other issues from ecological, cultural, or organizational perspectives. Public support and trust in governance processes are essential components in enacting effective policy changes that can help prevent, manage, and adapt to evolving plant health risks. Initiatives with diverse actors will be meaningful if they allow time for active participation and deliberation. The federal government has identified mobilizing a National Plant Health Information Network as a potential tool for collaboration, data sharing, and planning among key partners. The nascent Canadian Plant Health Council could be a useful way to develop and maintain such a network. Forward-looking exercises, such as scenario planning inclusive of both government and non-governmental actors, could help improve responsiveness and strengthen connections by identifying weaknesses within the plant health system before an actual crisis. There are numerous opportunities for involvement from various actors in the system, including Indigenous people, practitioners, industry organizations, and the general public. At the international scale, a global phytosanitary research network could align research agendas and accelerate the science that supports phytosanitary activities — a potential benefit to all actors in the plant health system, but especially to policymakers.

Final Thoughts

Threats to plant health are emerging rapidly under a changing climate. Additional threats are continually evolving through adaptation to current management practices and the increased movements of people and goods worldwide. While risks resulting from plant pests and environmental change are common to all ecosystems, the variety of organizational structures and jurisdictions called upon to address them also creates governance issues that threaten the robustness of the plant health system itself. Recognizing the commonalities and creating opportunities for sharing, coordination, and learning can help ensure gaps are identified and filled. Forward-looking exercises can stress-test the system and identify actions to reduce vulnerability and improve resilience in the face of increasing complexity and uncertainty. Biodiversity and redundancy in ecosystem functions are key to a resilient ecosystem — diversity in practices, tools, and perspectives is key to a robust risk management strategy. Canada is composed of vast, diverse landscapes, and therefore the scope of the challenge of protecting plant health is daunting. But plants are foundational to the economic, cultural, physical, and spiritual well-being of all people in Canada. Though many people may be unaware of the role plants play in their everyday lives, the ecological functions of plants support the basis for most life on Earth. However daunting, rising to the complex and urgent challenge of addressing risks to plant health is achievable and imperative for ensuring our collective future.

Abbreviations

AAFC	Agriculture and Agri-Food Canada
CBSA	Canada Border Services Agency
Council	Canadian Plant Health Council
CFIA	Canadian Food Inspection Agency
CFS	Canadian Forest Service
CPM	Commission on Phytosanitary Measures
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
DFO	Fisheries and Oceans Canada
ECCC	Environment and Climate Change Canada
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
ICE	Indigenous Circle of Experts
ISED	Innovation, Science and Economic Development Canada
IPCA	Indigenous Protected and Conserved Area
IPPC	International Plant Protection Convention
ISPM	International Standard for Phytosanitary Measures
NAFA	National Aboriginal Forestry Association
NAPPO	North American Plant Protection Organization
NRCan	Natural Resources Canada
OAG	Office of the Auditor General of Canada
OECD	Organisation for Economic Co-operation and Development
PA	protected area
PMRA	Pest Management Regulatory Agency
SFM	sustainable forest management
UN	United Nations
UNDRIP	UN Declaration on the Rights of Indigenous Peoples
WTO	World Trade Organization

Contents

1

Introduction

Canada is a land of plants — indeed, most of the country's landscape is covered by trees, shrubs, grasses, and agrarian crops. It is home to important biodiversity, including 28% of the world's boreal forests (NRCan, 2020a). Areas with relatively more tree cover span the west coast and southern interior of British Columbia, stretching to the boreal zone — an area of forest, woodland, wetland, and lakes that covers 550 million ha from the Yukon to Newfoundland and Labrador (StatCan, 2018). Land cover in the Prairies is made up mostly of crops and grasslands (StatCan, 2018).

Plants are inherently valuable to people in Canada and are a vital part of Canadian ecosystems. They provide habitat[1] for most of the biodiversity found in this country, make up most of the food we eat and the timber and fibre we use, help supply the oxygen we breathe, and are used in traditional and modern medicines. Plants also have social and cultural importance (e.g., aesthetics, ceremony, recreation, well-being) and underpin the fundamental relationship humans have with the natural world. Internationally, Canada's plant biomass (i.e., the renewable organic material humans consume as food or fuel, or rely on for carbon fixing) is an important contributor to global health. Canada has more wilderness than any other nation in the world (26%) — this wilderness, combined with the nation's size, make Canada the second-largest contributor to global carbon stores (Coristine *et al.*, 2019).

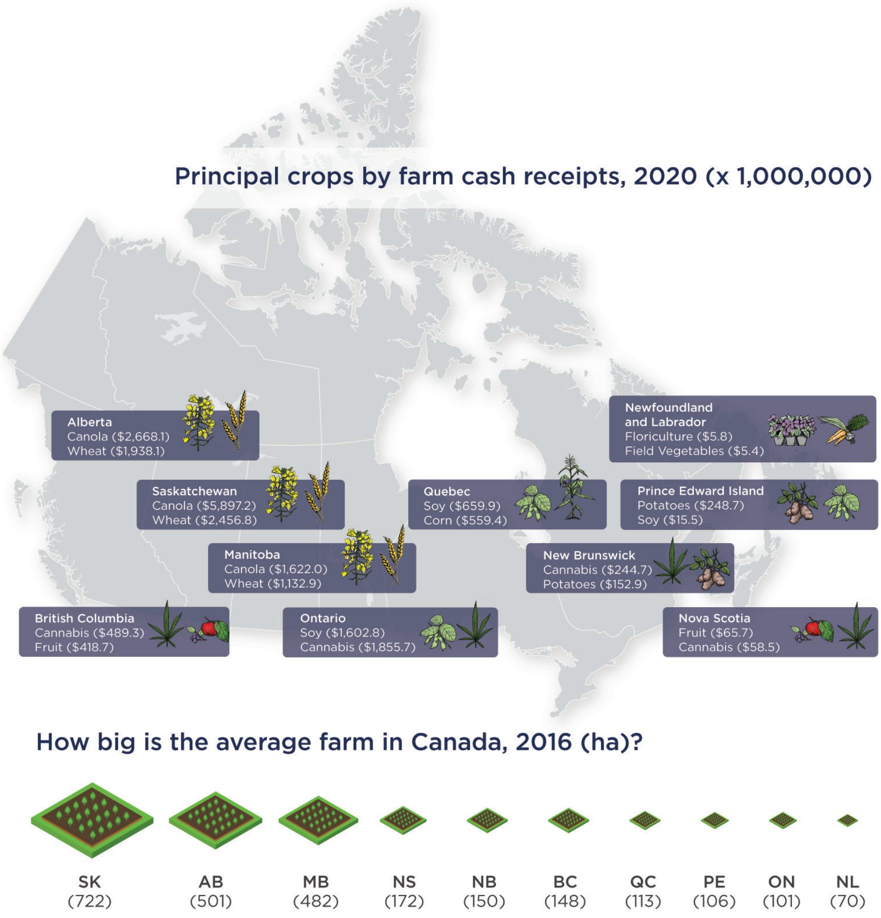
Because many authorities play a role in the governance of plant health in Canada, and because of the potential threats to Canada's plant health — including unprecedented shifts brought on by climate change — there is a need to understand and review risks to plant health, as well as potential responses in light of the importance plants have for everyone in Canada.

1.1 Agriculture and Forestry in Canada

Plants are vital to the Canadian economy. As of 2018, primary agriculture — that is, work done within a farm, nursery, or greenhouse — was responsible for 1.7% of Canada's overall GDP and employed 265,700 people (AAFC, 2020a). The agricultural sector varies by region; horticultural farms, for example, are more common in British Columbia and the Atlantic provinces, while grain and oilseed farms dominate in the Prairies (AAFC, 2020a). Canola (*Brassica napus*) farming is the largest agricultural contributor to Canadian GDP. The growth of canola seeds to produce oil is concentrated in the Prairies, making up a large share of the agricultural sector's GDP in the region (StatCan, 2019a). While the total area of land producing field vegetables has declined throughout Canada, greenhouse operations have increased, with the majority of production located in Ontario

1 "[T]he resources and conditions present in an area that produce occupancy — including survival and reproduction — by a given organism" (Hall *et al.*, 1997).

(AAFC, 2015). Finally, cannabis (*Cannabis sp.*) production has rapidly become a significant contributor to farm cash crops in several regions since its legalization in 2016 (StatCan, 2020b) (Figure 1.1).



Data Sources: StatCan (2016, 2019b, 2021c)

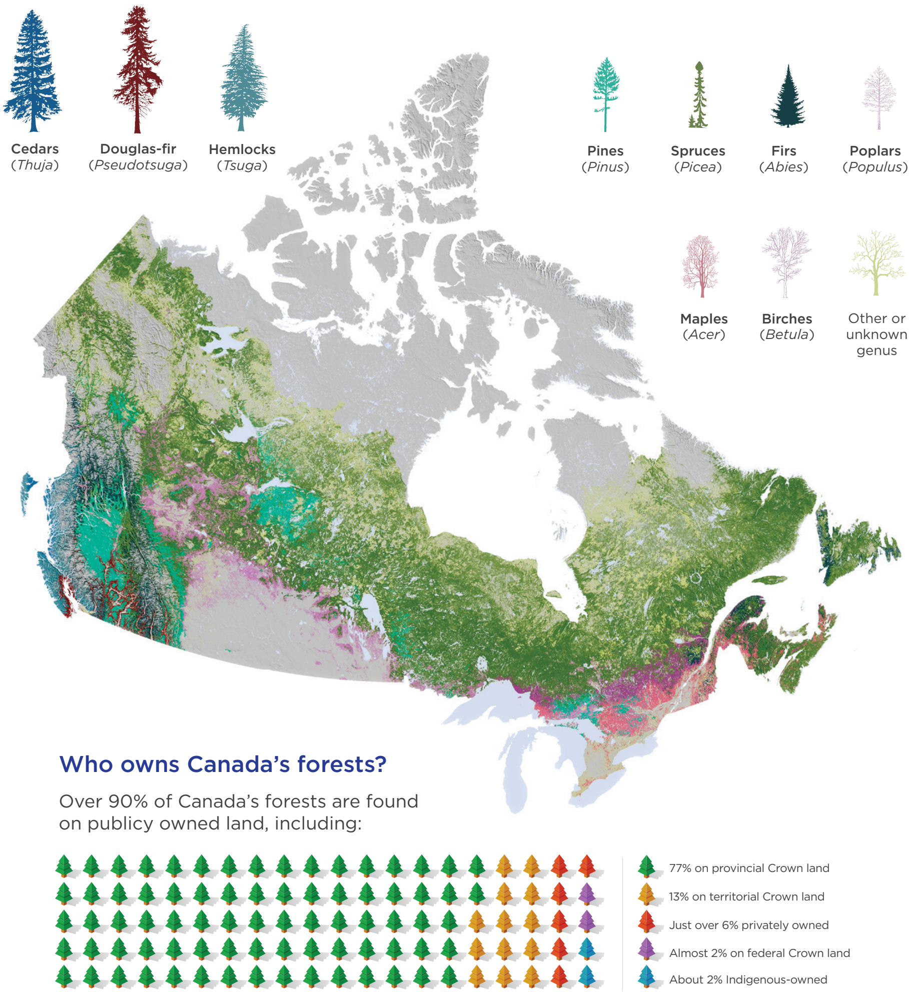
Figure 1.1 Principal Crops by Farm Cash Receipts and Average Farm Size, by Province

Horticultural crops (e.g., fruits and vegetables, as well as cannabis) are major crops in British Columbia and the Atlantic provinces, while large-scale grain farms are dominant in the Prairies, and soy is the principal field crop in Ontario and Quebec. Due to a dearth of arable land, the Northwest Territories, Nunavut, and the Yukon have not been included.

There has been a significant shift in farm sizes in Canada over the last half-century. According to Agriculture and Agri-Food Canada (AAFC), the size of farms has doubled, while the number of farms has decreased by half (AAFC, 2020a). The result of this shift is that a smaller number of farms create most of the revenue (AAFC, 2020a). Larger farms are predominant in the Prairies, while farms tend to be smaller in other parts of Canada (OMAFRA, 2017) (Figure 1.1). Farming approaches (e.g., levels of mechanization, reliance on inputs) may be tied to both the type of farm and its size, and may thus determine risks to plant health within a given operation (Therond *et al.,* 2017). In 2016, 75% of agricultural operations were registered as sole proprietorships and partnerships (down from 98% in 1971), and another 25% were incorporated family and non-family holdings (up from 2% in 1971) (StatCan, 2017a). While the presence of organic farms in Canada continues to rise overall, certified organic operations made up only 1.8% of all farms in Canada as of 2011 (StatCan, 2011).[2] The total export sales of agricultural and agri-food products reached $59 billion in 2018 (AAFC, 2020a).

Canada is home to 9% of the world's forests (NRCan, 2020k). Ninety-two percent of forests in Canada are publicly owned by federal, provincial, or territorial governments, while the remainder are either privately owned or Indigenous-owned (Figure 1.2). The forestry sector contributes 1.1% to Canada's nominal GDP and employs approximately 205,000 people. Work in the forestry sector is particularly important in many rural and Indigenous communities, and in 2020 was identified as the primary source of economic well-being for 300 communities in Canada. British Columbia is home to the most valuable forestry industry, followed by Quebec and Ontario (NRCan, 2020k). Exports of Canadian forest products are largely derived from coniferous trees and primarily include softwood lumber and wood pulp (NRCan, 2018). The value of exported forest products in 2019 amounted to $33 billion (NRCan, 2020k).

2 More recent data are unavailable, as the Census of Agriculture no longer asks respondents to indicate which of their products are certified organic (Isaac *et al.*, 2018).



Source: NRCan (2020k)

Figure 1.2 Composition and Ownership of Canada's Forests (2020)

Canada's forests contain many tree species, with different genera represented by different colours. Faded colours represent less densely forested areas, and silhouettes are shown for one species of each genus, to provide an indicator of the shape of trees found in different areas.

1.2 The Charge

Recognizing the importance of plants in maintaining a variety of economic and social goods — from food security to environmental sustainability to public health — and wanting to protect these goods, the Canadian Food Inspection Agency (CFIA) asked the Council of Canadian Academies (CCA) to convene an expert panel to provide an authoritative assessment of the risks to plant health in Canada. Specifically, the CCA was asked to answer the following question and sub-questions:

What are the most significant current and emerging risks[3] to plant health in Canada?

- What are the gaps in Canada's plant health system with respect to identifying and addressing current and emerging plant health risks?
- What promising and leading risk management practices, including indicators[4] and metrics,[5] could be used to improve the ability of Canada's plant health system to adapt and respond to current and emerging risks?

Plant health is the ability of plants to maintain their ecosystem functions.

1.3 Defining Plant Health and Related Risks

When they are healthy, plants provide benefits called *ecosystem functions*. A subset of these provide benefits to humans, and these are termed *ecosystem services*. Ecosystem functions can include supporting, provisioning, regulating, and cultural functions (Table 1.1). Their benefits can be environmental, socio-cultural, or economic, with considerable overlap among these categories (De Groot *et al.*, 2002). For example, soil regulation (a regulative function) maintains naturally productive soils and the organisms that are dependent on them (an ecological function), while also supporting the productivity of arable land (economic and social functions).

3 Of specific interest are risks associated with climate change, movement of people and goods, adoption of new crops and cultivation practices, and changes in land-use practices.

4 Indicators include those used to inform thresholds for tolerance to plant health risks.

5 Metrics include those used to assess the effectiveness of prevention or mitigation measures.

Table 1.1 Types of Ecosystem Functions and Ecosystem Services

Function Type	Examples of Goods and Services Provided
Provisioning	Food, wood, fibre, freshwater, fuel, genetic resources, biochemicals, natural medicines and pharmaceuticals
Regulating	Climate regulation, water regulation, water purification, disease control, air quality regulation, erosion regulation, pest regulation, pollination, natural hazard regulation (e.g., wetlands), soil regulation
Supporting	Nutrient cycling, primary production, photosynthesis, soil formation
Cultural	Aesthetics, cultural heritage/sense of place, education, recreation, spiritual and religious

Adapted from Millennium Ecosystem Assessment (2005) and Wall & Nielsen (2012)

The aesthetic good of protected land provides a social value that may be difficult or impossible to quantify, as it may be directly influenced by type of landscape or the people who are placing the value on it (L'Ecuyer-Sauvageau *et al.*, 2021). As noted by Skolrud *et al.* (2020), these valuations can also be contentious as "[t]here is no agreement in the literature about the correct method of valuing landscape aesthetics due to the extremely high degree of subjectivity among those living in the landscape and those that do not." There are, however, more easily quantifiable economic benefits related to aesthetics, including revenues from tourism and ecotourism, or the value of real estate within sight of, or a short distance from, visually pleasing areas (De Groot *et al.*, 2002).

There are many non-economic values that can be ascribed to plants. Environmental biodiversity, for example, has been shown to support linguistic and cultural diversity, with regions of high biodiversity hosting up to 70% of the world's languages (Gorenflo *et al.*, 2012; Luu, 2019a, 2019b). As discussed in Section 1.4.2, there are different paradigms in which to view plant health based on one's values. In turn, these paradigms influence one's understanding of what constitutes risks and the measures to alleviate them.

Risk can be defined probabilistically, where the likelihood of a hazardous event occurring is multiplied by the impact (or consequences) of the event (Rosa, 1998; CCA, 2019b). While this definition forms the basis for quantitative risk analysis, the Panel used a broader concept of risk — explored further in Chapter 2 — for this report. This broader concept includes any "situation or event where something of human value [in this case, plant health] has been put at stake and where the outcome is uncertain" (Rosa, 1998). Risks to plant health may impact the distribution and persistence of plant species across Canada; this can result in potentially devastating environmental, economic, and social consequences, including the inability of Indigenous Peoples to engage with and access the land in traditional ways important for the maintenance of their livelihoods and cultures. Risks such as insect infestation have always threatened plant health, but climate change, the globalization of trade, changes in land-use practices, and the adoption of new crops and cultivation practices all potentially exacerbate the severity and scope of risk impacts (Michelmore *et al.*, 2017).

In addition to having the potential for negative economic and human impacts, risks to plant health threaten biodiversity. To date, scientists have identified 72 endemic species of plants that are uniquely found in Canada (Enns *et al.*, 2020). The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) lists 23 vascular plants (i.e., plants other than mosses and liverworts) as at risk of extinction. As Enns *et al.* (2020) note, "[p] rotecting Canadian endemic species is Canada's responsibility and our first stop against global biodiversity loss. The consequences of our failure to conserve these species is their extinction."

Risks to plant health have the potential to negatively impact the ecosystem functions of a given plant or plant community, and can arise from an organism, system, or process.

1.4 The Panel's Approach

To answer the CFIA's charge, the CCA assembled a multidisciplinary panel of 14 experts (the Expert Panel on Plant Health Risks in Canada, hereafter the Panel). Panel members brought knowledge from agricultural and horticultural sciences, forestry, economics and trade, climate change, policy and regulation relating to plants, social impacts of plant health risks and risk mitigation strategies. Given the multidisciplinary nature of the Panel, members drew on varying perspectives to identify plant health risks and management solutions. In some cases, conclusions differed about approaches to identifying risks and solutions in this report; these are explicitly discussed as they arise. Each member served on the Panel as an informed individual rather than as a representative of a specific discipline, organization, region, or set of values.

Over the course of the assessment, the Panel met virtually 11 times to review evidence and deliberate on its charge. At the beginning of the assessment process, the Panel met with the CFIA to acquire a full understanding of the charge. At this meeting, the Panel confirmed that the primary focus of the assessment was to be plants of direct and immediate economic importance (i.e., agriculture and forestry), and that aquatic plants were out of scope. The Panel confirmed that, while its deliberations would specifically address risks to agricultural crops and forests, the assessment would also address significant broader risks to plants within terrestrial ecosystems across Canada.

1.4.1 Evidence

The Panel's assessment was based on a review of diverse sources of evidence, including peer-reviewed publications, publicly available government information and statistics, and grey literature related to current and emerging plant health risks, both within Canada and internationally. To find the best available evidence, the CCA staff conducted keyword-based searches of published literature and explored the websites of AAFC, the CFIA, Natural Resources Canada (NRCan), Environment and Climate Change Canada (ECCC), Parks Canada, Statistics Canada (StatCan), the Food and Agriculture Organization of the United Nations (FAO), and other relevant government agencies in Canada and abroad. This report is not based on a systematic review, but rather on a detailed analysis of key references identified by the Panel, which it felt represented the best available evidence on the topics discussed. The Panel was also informed by discussions with experts in the fields of ethnobotany, Indigenous natural resource governance, and international trade. The report underwent a comprehensive peer review, whereby an additional 13 experts from Canada and abroad provided further evidence and expertise.

1.4.2 Diverse Perspectives on Plant Health

Over the course of its deliberations, the Panel considered a variety of perspectives on the use and value of plants. It recognized that the plant health system in Canada is embedded within an international trading system that forms a significant part of the nation's economy. This system operates within a larger global framework that prioritizes the provisioning functions of plants that are typically valued in economic terms (FAO, 2021). From this perspective, plants are managed for economic returns. These returns can include food, fibre, and export commodities, and result in employment opportunities for many people living in Canada. This approach supports a specialized industrial food chain that has made food products affordable and accessible to consumers worldwide (Brodt *et al.*, 2011; FAO, 2017b). However, prioritizing economic returns has also inadvertently created or exacerbated certain risks to plant health (FAO, 2017b). For example, agricultural areas with less diversified crops, or employing practices that decrease diversity, have helped to create economies of scale and produce high volumes using simplified production processes (Abson *et al.*, 2013); however, they also help drive the emergence and spread of pest outbreaks (e.g., Fones *et al.*, 2020; Strelkov *et al.*, 2020).

While acknowledging the dominant system in which Canada currently operates, Panel members also wish to underscore that there are many ways to approach and manage plant health. For example, consideration of ecosystem functions or social values above production values results in a different framework for understanding risk, and in different approaches to protecting plant health, than those resulting from a solely economic valuation. The former may not only consider biological threats to plant health, but also how social, economic, and cultural forces within the current agricultural and forestry production systems contribute to plant health risks or further exacerbate them (CIP, 2021).

> The **plant health system** refers to the governance of plant health throughout Canada. This system is diverse; it contains many actors with different values and priorities, both governmental and non-governmental.

A combined perspective — one that prioritizes economic and ecological values on par with one another — may provide additional benefits, such as the increased resilience of ecosystems, supports for biodiversity and land conservation, and climate change mitigation (Lin, 2011; Abson *et al.*, 2013; Benton *et al.*, 2021). Potential approaches that incorporate both economic and ecological values include a renewed focus on agroecological methods for farm and forestry management, such as small-scale, organic, and diversified farming (Benton *et al.*, 2021); technological solutions (The Royal Society, 2009); land management decisions in forests that are rooted in community forestry and that support local conditions (Teitelbaum, 2015); and approaches that promote the diversification of tree species in an effort to improve forest resilience (Messier *et al.*, 2019). Approaches may also include incentives to balance production with restoration and conservation in order to maintain biodiversity and subsequent ecosystem resilience (Kline & Dale, 2020).

In this report, the Panel considered Indigenous perspectives of plant health. Indigenous worldviews prioritize biodiversity and the principle of reciprocity (e.g., Alfred, 2007). Humans derive many benefits from plants (e.g., food, medicines, aesthetics) and, as the beneficiaries, it is our responsibility to respect, and to be caretakers of, the natural world. Land is viewed not as a right but as a gift with responsibilities attached (Kimmerer, 2013). Indigenous worldviews also stress the interconnectivity and sacredness of all lifeforms. This philosophy, sometimes termed *kincentricity* or *kincentric ecology*, stresses the importance of relationships and that humans are a part of a broader ecological family (Martinez, 2008; Turner, 2016). From this perspective, it is only when this relationship between humans and the rest of the natural world is acknowledged that a truly healthy environment can be achieved. Indigenous relationships with plant health, and the incorporation of Indigenous knowledge in identifying and managing plant health risks in Canada, are explored in detail in Chapter 6.

1.5 Governance of Plant Health in Canada

The protection and management of risks to plant health in Canada is a multi-jurisdictional effort that involves international, federal, provincial, territorial, and municipal governments (Table 1.2), as well as a wide range of other actors including Indigenous rights-holders, non-government organizations (NGOs), farmers and woodlot owners, industry, and academia (Figure 1.3).

Table 1.2 Governing Jurisdictions and Their Roles in Protecting and Managing Plant Health in Canada

Partner	Role
International Governments and Organizations	• Set import requirements, verify export requirements • Compare and approve relevant systems (e.g., inspection) • Develop international science-based rules and standards
Federal Departments and Agencies	• Protect plant resources from pests, diseases, and invasive species • Prevent and manage food safety risks • Facilitate market access for Canada's food and plants
Provincial, Territorial, and Municipal Governments	• Enforce jurisdictional food safety and plant health requirements • Prevent and manage plant health emergencies • Preside over forestry management and urban landscapes

Adapted from CFIA (2017b) and NRCan (2020m)

1.5.1 International Agreements and Legislation

Canada's plant health system is informed by, and accords to, international and regional standards and agreements. Some of the most important agreements and organizations that determine Canada's roles and responsibilities in plant health are detailed in Table 1.3.

Table 1.3 International Organizations and Agreements Related to Plant Health

Agreement/Organization	Purpose
Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) **Administered by WTO*	Affirms Canada's commitment to using international standards based on scientific evidence to prevent the spread of pests and diseases among plants and animals.
International Plant Protection Convention (IPPC) **Administered by FAO*	Affirms international cooperation in protecting global plant resources (wild and cultivated) from pests, in the interest of global food security, biodiversity, and trade.
Commission on Phytosanitary Measures (CPM)	Governs the IPPC by gathering national representatives together annually to identify emerging plant health risks and to exchange relevant information.
International Standards for Phytosanitary Measures (ISPMs)	A set of non-legally binding guidelines adopted by the CPM that are designed to protect the environment, biodiversity, sustainable agriculture, and food security, while also facilitating trade and development.
International Forestry Quarantine Research Group (IFQRG)	Supports the work of the IPPC by responding to high-priority international forestry issues related to invasive species and quarantine.
North American Plant Protection Organization (NAPPO)	Commits Canada to trilateral cooperation with Mexico and the United States to prevent the entry, establishment, and spread of regulated pests in North America, and facilitates trade in plants and plant products in the region.
Committee on Sanitary and Phytosanitary Measures **Part of the Canada-United States-Mexico Agreement (CUSMA)*	Elaborates on the SPS Agreement by enhancing information exchange among nations and committing to science and risk-based analyses and transparency in the region.
Commission for Environmental Cooperation (CEC)	Facilitates regional cooperation among Canada, Mexico, and the United States to promote sustainable development and protect the North American environment.
North American Invasive Species Network (NAISN)	A regional effort (Canada, Mexico, United States) to improve coordination, communication, and collaboration in the management and prevention of invasive species on the continent.

Sources: WTO (1995); Allen & Cree (2003); GC (2009); Ackleson & Kastner (2011); NAPPO (2011); GC (2019a); ECCC (2020b); FAO (2020b); FAO & IPPC (n.d.-a, n.d.-b); IPPC (n.d.)

1.5.2 Federal Departments and Agencies

The CFIA is responsible for protecting plant health in Canada

The CFIA, a federal regulatory agency created in 1997, is tasked with protecting the plant resource base, the environment, and plant-related industries in Canada (CFIA, 2018b, 2019e). The CFIA therefore has two key roles relevant to this report: (i) the protection of plant health, and (ii) facilitating market access for Canada's plants and food (CFIA, 2019e). Within the CFIA, the Plant Protection Program (PPP) monitors, assesses, tracks, and eradicates plant pests, including invasive species (CFIA, 2015). The PPP's work includes "regulating agricultural and forestry products; mitigating risks to the plant resource base (including crops and forests) from regulated plants and diseases; regulating the safety and integrity of seeds, fertilizers, and plant products; and managing plant health emergencies and incidents" (CFIA, 2015). The work of the PPP has increased as a rise in international trade and travel, along with the impacts of climate change, increase potential risks to plant health, thereby increasing the demand for expertise in conducting research, surveillance, and risk assessments, and in communicating these findings to policymakers and the public (CFIA, 2015).

The CFIA supports 13 diagnostic and research laboratories, as well as a staff of over 6,000 people, including inspectors and scientists (Cision Canada, 2021). In 2021, the Government of Canada announced an investment of $163 million to the CFIA over the next five years, as well as an ongoing increase of $40 million of annual funding. These funds have been earmarked for the support of export certifications (i.e., improving inspection and certification times of agricultural products); the oversight of imports (i.e., increasing the number of import inspections and refocusing on prevention); domestic oversight and surveillance (i.e., creating up-to-date and multi-jurisdictional response plans for existing and potential plant pests and diseases); and digitization (i.e., expanding access to automated tools for inspection and risk management) (Cision Canada, 2021).

CFIA responsibilities are overseen by the Minister of Agriculture and Agri-Food and the Minister of Health. While the Minister of Health "is responsible for the overall direction of the CFIA and for all activities related to food safety," the Minister of Agriculture and Agri-Food leads the protection of plant health (CFIA, 2019b). The Ministers are directed to work together on issues of crossover significance (e.g., pesticide regulation) (PMO, 2019). The CFIA is responsible for administering four key pieces of legislation relating to plant health (Table 1.4). In addition, the *Agriculture and Agri-Food Administrative Monetary Penalties Act* establishes a penalty system that gives the CFIA additional means to ensure compliance with legislation, while the *Feeds Act* and the *Health of Animals Act*, also administered by the CFIA, serve an important role in ensuring the safety of food, including the regulation of novel traits[6] in human and animal food supplies (CFIA, 2019b).

Table 1.4 Plant Health Legislation Administered by the CFIA

Legislation	Purpose
Fertilizers Act	Regulates the import and sale of fertilizers and supplements (including biological and chemical), and provides for authority to prescribe standards, enforce packaging and labelling requirements, and inspect and sample products for compliance purposes.
Plant Breeders' Rights Act	Protects plant breeders' rights (a form of intellectual property rights) related to propagating material. This includes seeds for sowing and any part of the plant that may be used for propagation.
Plant Protection Act	Regulates the import, export, and spread of pests that are injurious to plants, and provides for their control and eradication and for the certification of plants.
Seeds Act	Regulates the quality standards, grades, and labelling requirements for seeds sold in Canada and provides the authority to inspect and sample seeds for compliance purposes and for the registration of varieties. This includes plants with novel traits.

Adapted from CFIA (2019b)

The Canadian Forest Service manages the forestry sector at a federal level

While forest resources are included within the CFIA's core responsibilities for plant health, federal management of the forestry sector falls to NRCan, which operates the Canadian Forest Service (CFS) and works with its provincial and territorial counterparts (FAO, 2003). The CFS operates six forestry research centres across the country and its scientists provide expertise on a range of topics, including pest identification, climate change, monitoring, biodiversity, and conservation (NRCan, 2020g). This research is intended to provide the scientific basis for informed decision-making by both land managers and policymakers (NRCan, 2020g). While the CFS is the national authority and international representative for Canada's forestry sector (NRCan, 2020g), provinces and territories have jurisdiction over most forests within Canada and are responsible for creating and enforcing many of the policies, regulations, and laws that govern forest management (NRCan, 2020m). Opportunities for discussion and exchange of ideas among federal, provincial, and territorial authorities are available

6 A plant with a novel trait is defined by CFIA as one that "contains a trait which is both new to the Canadian environment and has the potential to affect the specific use and safety of the plant with respect to the environment and human health" (CFIA, 2020b).

through the Canadian Council of Forest Ministers (CCFM) (CCFM, 2021b). The CCFM includes an Indigenous Engagement Committee directed at building partnerships with Indigenous communities and their leaders (CCFM, 2021a).

There are areas of shared responsibility within the federal government that relate to plant health

The CFIA's mandate is extensive and has many areas of crossover with other federal agencies. As noted, Health Canada and AAFC have a shared responsibility. The CFIA works with Health Canada in areas related to food-producing plants, especially those with genetic modifications (CFIA, 2015). The CFIA also works with the Pest Management Regulatory Agency (PMRA), a branch of Health Canada, to ensure the safety of pesticides used in Canada (CFIA & PMRA, 2000). AAFC supports the CFIA in its work specific to agriculture by providing research (especially as it relates to crop pests) and by formulating emergency and non-emergency responses to invasive species of plants and pests (CFIA, 2015). The CFIA also works collaboratively with AAFC on issues related to global trade in agricultural products (CFIA, 2015).

In addition to the joint efforts of the federal agencies described above, the CFIA works closely with the Canada Border Services Agency (CBSA) on biosecurity enforcement; with Global Affairs Canada on issues concerning international trade; with the Canadian Grain Commission (CGC) in formulating policies related to the grain industry; with Parks Canada and ECCC on issues related to ecosystem threats posed by invasive species, and on identifying plant health risks and mitigation strategies related to climate change; and with Innovation, Science and Economic Development Canada (ISED) and the National Research Council of Canada (NRC) on the development of innovative technologies (CFIA, 2015, 2017b).

1.5.3 Provinces, Territories, and Local Governments

Provinces, territories, and municipalities are an essential part of the collaborative network of partners tasked with protecting plant health (CFIA, 2017c, 2019c). Federal, provincial, and territorial ministries create regulations pertaining to plant health (Gov. of QC, n.d.-a). These regulations are informed by committees, such as the Canadian Plant Health Council (Box 1.1). These committees are typically made up of representatives with expertise in issues related to plant health, who come together in working groups, and whose recommendations are then brought forward and considered by policymakers. In the case of the CFIA, the agency coordinates with provincial and territorial ministries of agriculture, environment, and forestry in setting priorities, cooperating with surveillance efforts aimed at the early detection of invasive plant pests, responding to emergencies, and enforcing jurisdictional plant health requirements (CFIA, 2017b, 2019d; Canadian Plant Health Council, 2019).

Among Canada's provinces and territories, efforts aimed at managing plant health risks are variable. While every province and territory has a basic level of protection (i.e., the employment of conservation and wildlife officers), some possess more robust systems of risk surveillance, monitoring, and management than others. For example, Saskatchewan's Pest Biosecurity Program is focused on early detection and rapid response, and it collaborates with the Saskatchewan Association of Rural Municipalities (SARM) to provide services for the control of invasive species in rural municipalities and Indigenous communities (Gov. of SK, n.d.).

Box 1.1 The Canadian Plant Health Council

The Plant and Animal Health Strategy for Canada (hereafter the Strategy) was co-developed by the federal, provincial, and territorial governments, industry, academia, and NGOs (CFIA, 2017c). The goal of the Strategy is to safeguard Canada's plant and animal resources from existing and emerging risks to their health through preventative strategies and collaborative responses. Its mandate includes agriculture, forestry, aquaculture, and apiculture (i.e., beekeeping) industries (CFIA, 2017c).

The Canadian Plant Health Council (the Council) was created in 2018 to implement the Strategy's goals as they relate to plant health (CFIA, 2018c). The Council includes members representing federal, provincial, and territorial governments, industry, and academia; notably absent, however, is representation from Indigenous communities. Its mandate is to prioritize key plant health-related activities, respond to emerging needs, and facilitate cooperation among actors in order to identify preventative approaches to protect plant health (CFIA, 2018c). To accomplish this, the Council formed separate working groups focused on surveillance, biosecurity, and emergency response activities (Canadian Plant Health Council, 2019) (explored further in Section 5.1.2).

1.5.4 Other Actors Working Within the Canadian Plant Health System

While decisions affecting plant health have traditionally been made in government departments that incorporate the views of policy advisors and scientists, there is growing recognition that decision-making is strengthened through a broader community of actors representing a diversity of viewpoints. As summarized by MacLeod *et al.* (2010), "[t]here is now widespread acknowledgement that while evidence-based policy must be based on the best science, it must also take account of wider social and economic contexts in which that knowledge is set and used." For example, critical day-to-day decisions on plant health are often made in the field by farmers and foresters, and this experiential knowledge can strengthen and inform policies and regulatory frameworks. Figure 1.3 describes additional actors that have been identified by the Panel as key voices in the plant health system.

In addition to international, federal, provincial, territorial, and municipal governments (which authorize laws, policies, regulations, actions, and agreements), other actors possess expertise on plant health risks in Canada. These include:

NGOs
NGOs in Canada work on a breadth of issues related either directly or tangentially to plant health. NGOs often serve as collaborators with federal, provincial, and territorial governments and can be especially important at the local level as key communicators between other actors and policymakers.

Indigenous Governments and Rights Holders
Indigenous Peoples hold intimate knowledge and live in reciprocal relationships with plants. Indigenous Peoples in Canada hold rights; in some cases where there are no agreements and treaties with the Crown, Aboriginal title to land is protected by the Constitution.

Academia
The academic community advances the field of plant health through research, innovation, and knowledge transfer. Research informs public policy and provides the scientific underpinning to support phytosanitary legislation and regulation.

Farmers and Woodlot Owners
Farmers and woodlot owners safeguard plant health in the choices they make and the practices they follow, such as monitoring and reporting pest infestations, or adopting environmentally sound best practices.

Consumers and Citizens
Consumers signal their preferences with their purchasing power, while citizens signal their preferences through advocacy and voting power, which in turn influences legislation.

Industry and Trade Associations
Many Canadian forestry- and agriculture-based industries are represented by trade associations, trade boards, and grower groups. They work with the CFIA to maintain and implement plant health standards, promote and protect industry interests while meeting federal guidelines, and lobby to shape regulatory frameworks and trade laws. Industry also plays a key role in developing technologies.

Sources: McNeil (2002); Pautasso *et al.* (2012); Turner *et al.* (2012); ISED (2013); JUS (2018); CFIA (2019c); FAO (2019b)

Figure 1.3 Actors Relevant for Plant Health Risk Management in Canada

International, federal, provincial, territorial, and municipal governments can ensure that plant health risks are identified and assessed with the best possible information by coordinating with and including the input of other actors, such as Indigenous governments and rights-holders, industry and trade associations, farmers, woodlot owners, NGOs, academia, and the public.

1.6 Report Structure

The Panel developed a framework for categorizing significant and emerging plant health risks in Canada, which is reflected in the structure of the report. **Chapter 2** provides the risk context for plant health. It introduces climate change, the movement of people and goods, and evolutionary processes as important drivers of plant health risks. Chapters 3 through 6 offer insight into how these factors affect the likelihood and impacts of risks to plant health and review promising practices that may help to mitigate risks to plant health in Canada. **Chapter 3** examines how environmental changes, particularly those driven by climate change and land-use practices, exacerbate existing plant health risks, while **Chapter 4** examines how the risk pests pose to plant health changes due to these exacerbating factors. Governance risks to plant health are discussed in **Chapter 5**, which examines threats that arise within the context of the plant health system in Canada. Included among these risks are those associated with a lack of coordination and communication among actors in the system, emerging technologies, and issues related to public trust (or a lack thereof) in governance. **Chapter 6** provides an overview of Indigenous Peoples' rights and roles in plant health, including a description of Indigenous worldviews on stewardship and land use, as well as contemporary Indigenous approaches to land management and the ways in which Indigenous knowledge can be included in Canada's current plant health system. Lastly, **Chapter 7** answers the charge and provides the Panel's final reflections.

2

Understanding Risks to Plant Health

Chapter Findings

- Plant health reflects the relationships among the plant, its environment, and its pests, all of which are influenced by exacerbating factors and the choices people make as individuals and as a society.
- Risks to plant health vary from well known and predictable, to risks for which the likelihood and outcomes may be difficult to predict, to speculative risks that are plausible and potentially catastrophic, but may never materialize.
- Exacerbating factors, such as climate change, the movement of goods, and evolutionary processes, can increase the complexity, uncertainty, and ambiguity associated with identifying and responding to plant health risks.
- The vulnerability of a plant ecosystem influences the likelihood of a risk manifesting and the potential severity of outcomes. Vulnerable ecosystems tend to be tightly coupled, with few barriers to the spread and propagation of adverse events such as pest outbreaks.
- Resilient plant ecosystems are those able to retain or recover function following a hazardous event; resilience is linked to biodiversity and redundancy in ecosystem function.

Plants, like all organisms, do not exist in isolation. Their lives and deaths are embedded in complex relationships with both their living (biotic) and non-living (abiotic) environments. It is through the strength of these relationships that plants may withstand or adapt to changes or stress. Identifying and assessing a risk to plant health depends on the ability to quantify both the likelihood and the impacts of a specific threat. For this report, *impacts* are defined as the outcomes of hazardous events (e.g., a disease or predation event) that negatively affect the ecosystem functions plants provide.

2.1 Plants, Pests, and the Environment

The plant disease triangle describes three main factors that interact to determine plant health: host, pathogen, and environment (Agrios, 2005). Mitigation and management of plant health are therefore part of an integrated process; specific efforts may target either the environment, pathogen, or host, and these efforts are used in concert to bolster the overall health of a plant population (Agrios, 2005). To broaden the plant disease triangle to include all plant health risks, the Panel considered pests other than pathogens (i.e., competitors and predators), as well as exacerbating factors that influence both the likelihood and the potential consequences of risks to plant health (Figure 2.1). Thus, plant health is a function of the relationships among the plant itself, the components of its environment (e.g., temperature, precipitation, soil conditions, pollinator communities) and its pests. Both the individual components of plant health, as well as the relationships among them, are influenced by exacerbating factors, such as climate change, the movement of goods, and evolutionary processes. All components of plant health, as well as exacerbating factors, are influenced by the choices people make as individuals and as a society.

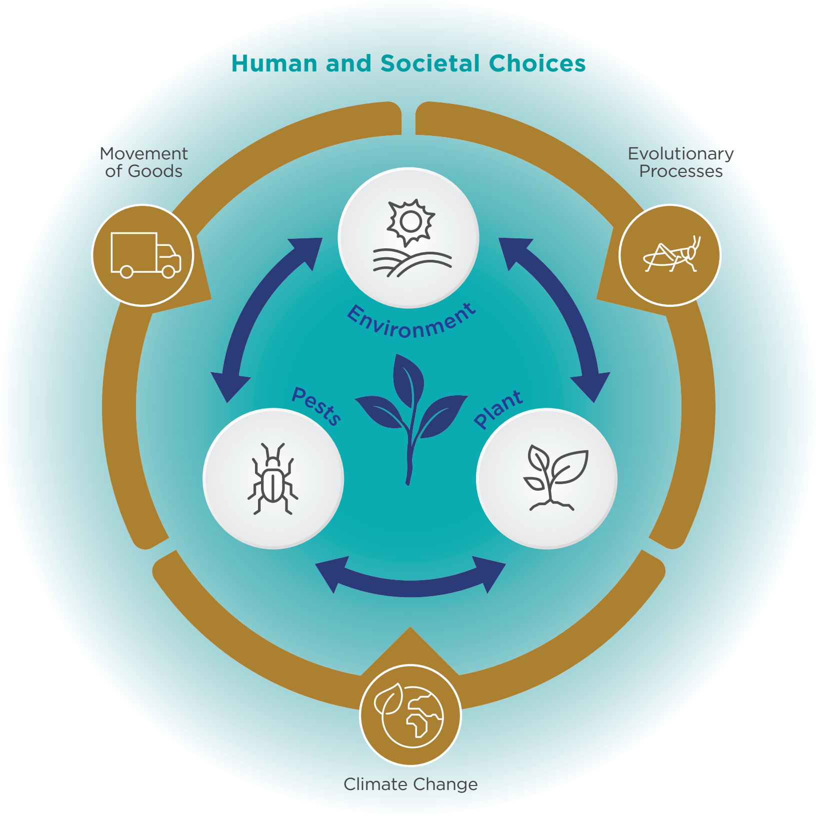


Figure 2.1 Risks to Plant Health Reflect Complex and Dynamic Relationships Among Plants, Pests, and Their Environment

The choices people make, as individuals and as a society, affect exacerbating factors, such as climate change, movement patterns, and evolutionary processes, but can also affect the components of plant health (the plants themselves, their pests, and their environment) and the relationships among them.

Total elimination of risks to plant health is neither possible, nor desirable. The loss of plants to disease and predation is important for ecosystem functions such as nutrient cycling and supporting biodiversity (NRCan, 2020k). Plant health risks are of concern when additional factors — such as plant population size, changes in environmental conditions (e.g., temperature, humidity), extreme weather events, alterations in plant communities, or a lack of co-evolutionary history, among others — lead to rapid and substantial damage or loss of ecosystem functions (NRCan, 2020k). Exacerbating factors can shift our understanding of plant health risks by introducing uncertainty and complexity when estimating the likelihood and impacts of specific threats. For example, climate change can alter the environment for both plants and pests, and their respective responses to changing climatic conditions are in turn influenced by evolutionary processes (e.g., strength of selection pressures). Plants co-exist with pest species — pathogens, predators, and competitors that can cause direct and indirect harm — and pest species themselves face pressure from their own predators, competitors, and pathogens (Box 2.1).

Box 2.1 What Are Plant Pests?

Plant pests are defined as any organism "that is injurious or potentially injurious, whether directly or indirectly, to plants or to products or by-products of plants" (GC, 1990). These include:

- disease-causing organisms (**pathogens**) that alter the normal physiological processes of plants, leading to partial or complete plant death; these are generally microscopic or sub-microscopic. Plant pathogens include fungi and fungi-like organisms, bacteria, viruses, and other parasitic organisms (Burchett & Burchett, 2018);
- organisms that have a detrimental impact on plant health through physical damage or direct consumption, including parasites (**predators**). Economically important invertebrate pests include arthropods (e.g., insects, mites) and nematodes (i.e., roundworms). Vertebrate pests (e.g., deer, geese, mice) eat or damage standing crops (Burchett & Burchett, 2018; FAO, 2019a); and
- weeds (**competitors**), which are plants growing where they are unwanted, but more specifically that reduce yield or quality in plant populations of economic, ecological, or cultural significance (e.g., crops, forests) (Khan *et al.*, 2019a; Chauhan, 2020).

2.1.1 Exacerbating Factors

Challenges in assessing plant health risks include exacerbating factors that can increase the volume of and rapidity with which new threats arrive in Canada and alter current plant–pest relationships. These factors can introduce uncertainty and complexity into the evaluation of risks that were previously believed to be well known and predictable.

Evolutionary processes alter plant health relationships across generations

Living systems are dynamic — they fluctuate around equilibria under continual disturbances (Gunderson & Holling, 2002). Managing biotic risks to plant health is a substantial challenge, as living systems are inherently changing through time. No one tool for mitigating biotic plant health risks will work indefinitely or consistently in all situations. Agriculture manipulates the relationship between plant species and their habitats, as humans intervene to maximize production through alterations to the biotic and abiotic environments and to the plant itself. These alterations can further impact other organisms that inhabit a given area, such as weeds, insects, and soil microbes, by changing selection pressures on crops and their pests, adding further complexity to the management of these dynamic systems (Owen *et al.*, 2014). Forest management practices likewise contend with the dynamic nature of biotic systems. For example, native tree pathogens may be relatively ubiquitous across a species' range, and outbreaks of disease may be linked more to environmental changes that increase susceptibility (e.g., drought) than to the presence of the pathogen itself (NRCan, 2018). In Canada, Armillaria root disease is caused by a native fungus, and its spread is influenced by weather; a hotter, drier summer (which increases potential water loss in the growing season) correlates to higher mortality in young lodgepole pine (*Pinus contorta*) from the disease, whereas warmer spring weather correlates with lower mortality (Dempster, 2017). The impacts of climate change, as well as changes in forestry practices and ongoing introductions and range expansions of non-native species through introductions by international and domestic trade and travelers, further complicate the understanding of the evolutionary processes at play in forest ecosystems.

Climate change impacts plant health and alters plant-pest relationships

Canada's climate is changing. Since 1948, the average temperature in Canada has increased by approximately 1.7°C on land — close to double the global average (GC, 2019b). In addition to temperature, precipitation in Canada has increased overall and is expected to continue to increase, although not uniformly across the country. An increase in extreme weather events is also linked to the changing climate, and such events are difficult to predict, plan for, and manage (GC, 2019b). Climate change has had direct impacts on plant health by changing the abiotic environment and has also affected the relationships between plants and insects in observable and measurable ways. Warming temperatures have led directly to observed increases in the size of some pest populations and changes in plant-pest relationships (DeLucia *et al.*, 2012). Elevated CO_2 levels are changing plant hormones, which can make plants more susceptible to chewing insects (Zavala *et al.*, 2017). While elevated CO_2 levels can also slow insect development, higher temperatures accelerate it — particularly in temperate ecosystems, climate change may result in an increase in the number of generations of insect herbivores each year (Hamann *et al.*, 2020).

Climate change can also support the establishment of novel pests, arriving via natural dispersal mechanisms (e.g., wind, water, animals) or brought in via travel and trade. In some cases, a lack of natural enemies and native plant defenses against these new pests can result in rapid population growth, with pests potentially harming host plants, but also causing damage to ecosystems and agricultural production and output (Lopian, 2018). Climate change is expected to enable more frequent and more severe outbreaks of plant pests, resulting in significant plant mortality (GC, 2014a). Weeds may establish in new areas, and climate change can make the conditions within their current ranges more favourable, increasing their competitive advantage over crops (Grain Farmers of Ontario, 2019). In North America, ranges for many weed species are expanding northward to regions that were once considered too cold for successful reproduction, including Canada (Clements *et al.*, 2014). Climate-induced changes in weed-crop competitiveness could make some weeds more difficult to manage (Peters *et al.*, 2014; Grain Farmers of Ontario, 2019), increase the cost of weed control (Korres *et al.*, 2016), and lead to additional yield or quality losses (Clements *et al.*, 2014).

The movement of people and goods increases the likelihood of new pest introductions

The impacts of plant pests can be staggering in both economic and environmental terms. Crop losses from plant diseases cost the global economy US$220 billion annually (Agrios, 2005), while invasive species cost upwards of US$70 billion (Bradshaw *et al.*, 2016). Globally, trade is a major contributor to the spread of invasive pests, as well as the introduction of novel pests (MacLeod *et al.*, 2010). Approximately 58% of invasive plant species established in Canada were introduced intentionally as agronomic crops, landscape plants, ornamentals, or medicinal plants (CFIA, 2008a). The origins of over 80% of invasive plants in Canada can be traced to the West Palearctic region, largely Western Europe, reflecting historical trade and colonization routes along with climate suitability.

Current trade with the East Palearctic region (e.g., China, Japan) accounts for the second-largest group of invasive plant species (CFIA, 2008a). Invasive plant species cause harm in native plant ecosystems, as well as in agriculture and forestry operations; some can even be harmful to human and animal health. For example, prickly lettuce (*Lactuca serriola*) is native to Asia, Europe, and North Africa (Weaver & Downs, 2009). In Canada, it competes strongly with soybeans (*Glycine max*) during drought conditions and can reduce the quality and efficiency of winter wheat (*Triticum aestivum*) harvests. It can also be toxic to cattle that are feeding exclusively on fresh, young plants, and has been declared a noxious weed in Manitoba (Weaver & Downs, 2009).

Liebhold *et al.* (2012) estimate that nearly 70% of forest insect and pathogen introductions in the United States from 1860 to 2006 most likely arrived through the importation of live plants. The majority of introduced sap- and foliage-feeding insects, as well as approximately half of introduced forest pathogens, most likely came through live plant importation, while the majority of wood- and phloem-feeding insects were introduced through wood imports (including wood packaging). Examples of forest pests introduced from live plants include white pine blister rust (*Cronartium ribicola*) on imported pine seedlings from Germany in the early 1900s and, more recently, sudden oak death (*Phytophthora ramorum*), which emerged in California in the mid-1990s and has spread through nursery stock across the western United States and into Canada (Liebhold *et al.*, 2012). In addition to economic losses in agriculture and forestry, invasive plant species can cause economic harm to all land managers, including municipal governments. A 2018 survey of 88 responding municipalities and conservation authorities in Ontario reported spending approximately 13% of their annual species-specific expenditures (nearly $2.7 million) on invasive plant control, with over 75% of those funds going to control just three invasive plants: the common reed (*Phragmites australis*), wild parsnip (*Pastinaca sativa*), and European buckthorn (*Rhamnus cathartica*) (Vyn, 2019).

2.1.2 Predictable, Probabilistic, and Speculative Risks

Plant ecosystems depend on both abiotic components (such as mineral nutrients, temperature, and water) and biotic components (such as fungi, pollinators, and other plants) (Agrios, 2005; NRCan, 2020k). Environmental stressors such as low nutrient availability, changes in temperature, relative humidity, and light availability, as well as the character and quality of soil microbiomes and pollinator populations, affect plant health both alone (Chapter 3), and in combination with pests (Chapter 4). Some risks to plant health are relatively well known and predictable, and those making management decisions (such as farmers) can adapt their crops and cultivation strategies to mitigate negative outcomes.

Known pests, with established and available forecasting and management strategies, fit in this category. However, pests and environmental stressors can also interact with each other and create impacts collectively that differ from impacts where each stressor acts alone (Seidl *et al.*, 2017; Burchett & Burchett, 2018). For example, the spread of an invasive species and the evolution of pesticide resistance are both known risks to plant health; however, the timing and severity of these impacts vary depending on additional factors. Differences in pesticide use and cropping strategies can affect the evolution of pesticide resistance over time and in space. Similarly, climate and land-use patterns can affect the timing and scope of invasive species spread, as well as the resulting damage to native plant ecosystems. The challenge of predicting timing, location, and severity of impacts makes proactive mitigation strategies difficult to establish. Therefore, strategies to address such probabilistic risks include scientific research to better inform predictive models. For instance, understanding the population genetics of weed species can help predict their invasive potential or the relative effectiveness of control efforts (Clements *et al.*, 2004).

The Panel also notes that some risks are speculative — that is, there are known types of risks (e.g., disease outbreaks) that have not yet materialized (and may not in the foreseeable future), but their potential consequences are so catastrophic that many argue they cannot be ignored. However, given the multifaceted nature of the plant health system in Canada (Chapter 1), the Panel notes that the characterization of an outcome as *catastrophic* differs among sectors such as forestry, field cropping, horticulture, and natural ecosystems. The definition of a catastrophe may also vary depending on the scale at which the boundaries of the system are drawn, and how different ecosystem functions are valued. That is, a catastrophic failure in the plant health system may look very different depending on whether the scale is that of an individual farmer, logging company, or greenhouse operator; a provincial or territorial regulator; a national economy; or a global trade organization. Moreover, the loss of a plant species from a location may be regrettable to some but catastrophic to others, depending on the value placed on preserving biodiversity, or the impacts of this loss on other species or ecosystem services. In the plant health system, examples of such events could include the emergence or introduction of a pest that causes the extinction of one or more plant species, severe drought conditions that extend over multiple years, catastrophic flooding events, or the complete and ongoing failure of a previously productive crop. Risk management for such exceptional, but plausible, events can include scenario testing (i.e., examining risk outcomes and interactions over long time periods) and sensitivity testing (e.g., examining immediate responses to short-term shocks) (OSFI, 2009), though their application in the plant health system has been minimal.

2.2 Governance Factors

Vulnerability refers to the inability of the system to resist the impacts of an unwanted event and to restore itself to its original state or function following the event (Rausand, 2011).

Plant health risks do not solely derive from plants, the environment, and pests. The governance of the plant health system influences both the likelihood and potential consequences of hazardous events (Chapter 5). While governance risks to plant health are pervasive across all plant ecosystems, the potential consequences of governance failures are perhaps most starkly illustrated by tree-based systems because of their long lives and slower recovery times (as compared to annual cropping systems). For example, the unintended importation of a novel forest pest may lead to a new tree disease that damages regulating and cultural ecosystem functions, causing economic losses and environmental degradation. The likelihood of importation and establishment reflects not only dispersal capabilities and environmental suitability, but also the frequency with which potentially infected products are imported (a reflection of trade agreements and market demand, among other factors) and the effectiveness of surveillance and quarantine practices (a reflection of regulations and resources, among other factors). The potential consequences of a new tree disease are also influenced by system design, such as the use of a single type of shade tree in residential areas (Box 2.2), or a paucity of policies related to the domestic movement of potentially infested wood and wood products. Vulnerability and resilience are factors that influence the ability of a system to either avoid or absorb a hazardous event while maintaining function.

Systems that are complex and tightly coupled are more vulnerable to catastrophe

The plant health system is a complex architecture of local, sub-national, national, and global actors, intimately connected through trade; the interactions among these actors are further complicated by diverse goals (Chapter 1). *Complex systems* exhibit non-linearity, such that it is difficult to establish cause and effect among hazardous events and their potential consequences, with seemingly minor incidents combining in unknown, unanticipated, and/or unobservable ways (Perrow, 1999). While, biologically,

Resilience is the ability of the system to absorb shocks and accommodate change while maintaining function and avoiding failure (Rausand, 2011).

plant health risks are often complex and involve non-linear relationships as well as both direct and interactive effects, the human elements of the plant health system can also be a source of complexity. For example, a novel pest outbreak may go undetected to the point where eradication strategies are not feasible, not because of a lack of surveillance, but rather because of a lack of understanding and information flow due to unclear communication and coordination among a complexity of actors (Chapter 5).

Coupling reflects the extent to which elements of the system are connected to each other — that is, whether there is slack or a buffer between elements (Perrow, 1999). Tightly coupled systems, while often more efficient, also limit opportunities for intervention, isolation, and understanding when hazardous events occur. Incidents, failures, and errors happen in complex systems, and no preventative effort can be completely effective; thus, a further objective in avoiding catastrophe is having in place systems that can withstand such incidents (Perrow, 1999). Commonalities in the characteristics of systems susceptible to catastrophic failures can shed light on strategies for both recognizing potential issues and mitigating high-risk scenarios (Box 2.2).

Box 2.2 Examples of Catastrophic Losses in Plant Systems

Dutch elm disease

Dutch elm disease, caused by the fungal pathogens *Ophiostoma ulmi* and *O. novo-ulmi*, resulted in the loss of between 80 and 90% of American elm trees (*Ulmus americana*) from Montréal and Toronto in the 1970s (Rioux, 2003). The impacts of Dutch elm disease have been keenly felt by many residents of cities in eastern North America, where American elms were a frequently planted shade tree lining residential streets (Schlarbaum *et al.*, 1997). The loss of tree-lined boulevards went beyond the functional damage to suburban landscaping; its impact is notable in larger American culture. For example, a diseased elm tree's removal from the Lisbon family yard features prominently in the novel, and subsequent film, *The Virgin Suicides* (Eugenides, 1993).

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Panama disease

Panama disease is a disorder lethal to bananas (*Musa* sp.), caused by the soil-borne fungus, *Fusarium oxysporum* f.sp. *cubense* (Ploetz, 1994). As the global trade in bananas grew, so too did the spread of Panama disease among plantations in tropical areas around the globe (Ploetz, 1994), ultimately leading to the eradication of the Gros Michel cultivar in the 1960s and the abandonment of plantations throughout Africa and the Americas (Stover, 1962). The global banana trade survived through the development of a new, resistant cultivar, the Cavendish; however, a new variant of the fungus, known as tropical race 4 (TR4), is again threatening the survival of the global trade in bananas (Fones *et al.,* 2020). Estimates of the economic impact of TR4, while scarce, have been in the range of US$120 to US$240 million annually in Indonesia and Taiwan, respectively (Stockstad, 2019). The confirmation of TR4 in Colombian banana plantations in 2019 led to the country declaring a state of emergency (Galvis, 2019).

An inherent vulnerability in the plant health system in Canada is international trade — the importation of plant materials brings with it the potential introduction of new disease, insects, and weed species. Vulnerabilities may be reduced by using barriers (e.g., procedures, administrative controls) that prevent, control, or limit the harm caused by a hazardous event. Barriers may be proactive (i.e., prevent hazardous events from occurring) or reactive (i.e., stop or mitigate the consequences following a hazardous event) (Rausand, 2011). Mitigation is an action that reduces the severity, seriousness, or painfulness of a hazardous event (Rausand, 2011). Global trade in bananas, lumber, and the use of wood packaging facilitated the introduction of both Dutch elm and Panama disease pathogens to new geographic areas (Box 2.2). The CFIA is mandated to enact and implement actions that create barriers to such risks, including risk assessments, surveillance, and setting inspection targets (OAG, 2008). The planting of a single species or variety provides no buffer or barrier to slow the spread of disease among individual plants (Fones *et al.*, 2020). Both the global banana industry and the North American suburban landscape were tightly coupled by the dominance of one type of plant — plantations comprising only one variety of banana (Fones *et al.*, 2020) and neighbourhoods lined with only American elms (Schlarbaum *et al.*, 1997).

Biodiversity and functional redundancy can improve the resilience of ecosystems

Decreasing vulnerability in plant health systems is not always feasible. Increasing resilience — that is, improving the ability of a system to recover from hazardous events — is a complementary strategy. In financial theory, it is widely recognized that increasing the diversity of assets held in a portfolio distributes risk among those holdings, with a smaller profit for any single holding being the trade-off (Figge, 2004). This theory may have applications in managing risks to different plant ecosystems, where it is not the absolute number of species (or genes, or populations) that is of value, but rather the diversity in characteristics (i.e., variability or functional diversity) (Figge, 2004). Plant diversity has been found to drive ecosystem productivity and services (Tilman *et al.*, 2012; Liang *et al.*, 2016), and can also support other types of diversity, such as in leaf bacterial communities that contribute to plant community productivity (Laforest-Lapointe *et al.*, 2017).

Biodiversity is also a component of soil health, and soil health is an important determinant of resilience in plant ecosystems (Section 3.2). For example, symbiotic relationships between fungi (arbuscular mycorrhizas) and the roots of terrestrial plants are found among all phyla of land plants (Smith & Read, 2008), and the presence of such fungi is a determinant of plant biodiversity and productivity (Van der Heijden *et al.*, 1998; Schnitzer *et al.*, 2011). In temperate forest ecosystems, the herbaceous layer — vascular plants one metre or less in height — is the most diverse and can contain over 90% of the plant species in the forest (Gilliam, 2007). While representing less than 1% of the aboveground biomass in a forest, the herbaceous layer contributes substantially to ecosystem functions. It mediates carbon dynamics and energy flow in forests, influences the cycling of essential nutrients, and is a determinant of regenerative patterns of dominant overstory species (i.e., trees) (Gilliam, 2007).

Redundancy in ecosystem functions among species increases the resilience of ecosystems. All sexual reproduction in plants relies on biotic (i.e., animals) or abiotic (i.e., wind, water) agents for pollination (Bennett *et al.*, 2018). Crops such as apples (*Malus* sp.), blueberries and cranberries (*Vaccinium* sp.), sunflower (*Helianthus annuus*), and alfalfa (*Medicago sativa*) rely on insect pollination for production (Reilly *et al.*, 2020). In a study of apple orchards in Quebec, wild bee pollination produced greater fruit and seed set compared to pollination by rented honeybees (*Apis* sp.), likely due to the increased diversity in foraging behaviour and activity patterns (Teixeira-Martins, 2013). Diversity in pollinator species creates redundancies in pollination services, which helps buffer against losses among individual species under changing environmental conditions (Brittain *et al.*, 2013). Indeed, as Holling (1996) concludes, "[r]eduction of variability of living systems, from organisms to ecosystems, inevitably leads to a loss of resilience in that part of the system being regulated."

2.3 Approaches to Plant Health Risk Analysis

For decades, quantitative (or probabilistic) risk analysis has been the basis for risk-related decision-making in industry, and it involves answering three main questions (reviewed in Aven, 2020):

- What can go wrong?
- What is the likelihood of that happening?
- What are the consequences?

These three questions relate directly to the main steps of a risk analysis, which uses all available evidence to identify and characterize a risk (Rausand, 2011). The CFIA follows a risk analysis process that includes *risk assessment* (characterizing risk by likelihood and outcome), *risk management* (establishing options for mitigating the risk), and *risk communication* (contact with stakeholders throughout the process) (CFIA, 2014). Once the threats, their likelihoods, and their consequences have been identified (risk assessment), a risk management plan will be decided upon. This plan may include considerations of potential costs versus benefits of different mitigation strategies, the acceptability of the risk to potential victims, and the circumstances under which the risk may be more or less tolerable (i.e., availability of mitigation or management strategies) (Rausand, 2011; CFIA, 2014). In the management of plant health, the CFIA's risk analysis framework embeds the processes of risk assessment and management within risk communication, through strategies of open information, open data, and open dialogue, in order to increase transparency and facilitate the exchange of information (CFIA, 2014). These strategies are employed to improve the sharing of information, data, and dialogue among risk assessors, risk managers, and stakeholders and rightsholders throughout both the assessment and management phases (CFIA, 2014).

Complexity, uncertainty, and ambiguity challenge risk assessment and management

For many risks, quantitative approaches to risk assessment are limited by data availability and uncertainty; risk assessments must also rely on the qualitative judgments of experts in relevant fields (Aven, 2020). When the facts are uncertain, the legitimacy of quantitative estimates may be called into question, particularly when used to derive a key number (e.g., the statistical likelihood of a pest introduction or establishment) with a precision greater than is technically possible (Funtowicz & Ravetz, 1994). As well, such approaches to risk assessment do not fully address the ultimate purpose of most risk assessments, which is to inform policy decisions and public choices (Rosa, 1998). While technical assessments are integral to policy decisions, they can lack the consideration of judgment and tolerability that is necessary for risk evaluation (Klinke & Renn, 2012). As Rosa (1998) notes, "[s]cience is an essential but incomplete knowledge system for many of the environmental and other risk problems facing the world." Strategies that extend beyond the quantitative assessment of risk can help address complexity, uncertainty, and ambiguity in broader policy questions, such as those related to plant health (Box 2.3).

Box 2.3 Complexity, Uncertainty, and Ambiguity in Risk Analysis

Complexity reflects a difficulty in establishing causal links between events and outcomes because of a non-linear relationship between cause and effect. When cause and effect cannot be established through quantitative analysis, an agreement on the most likely cause and effect relationships can be generated by discussing the available evidence from a variety of related disciplines.

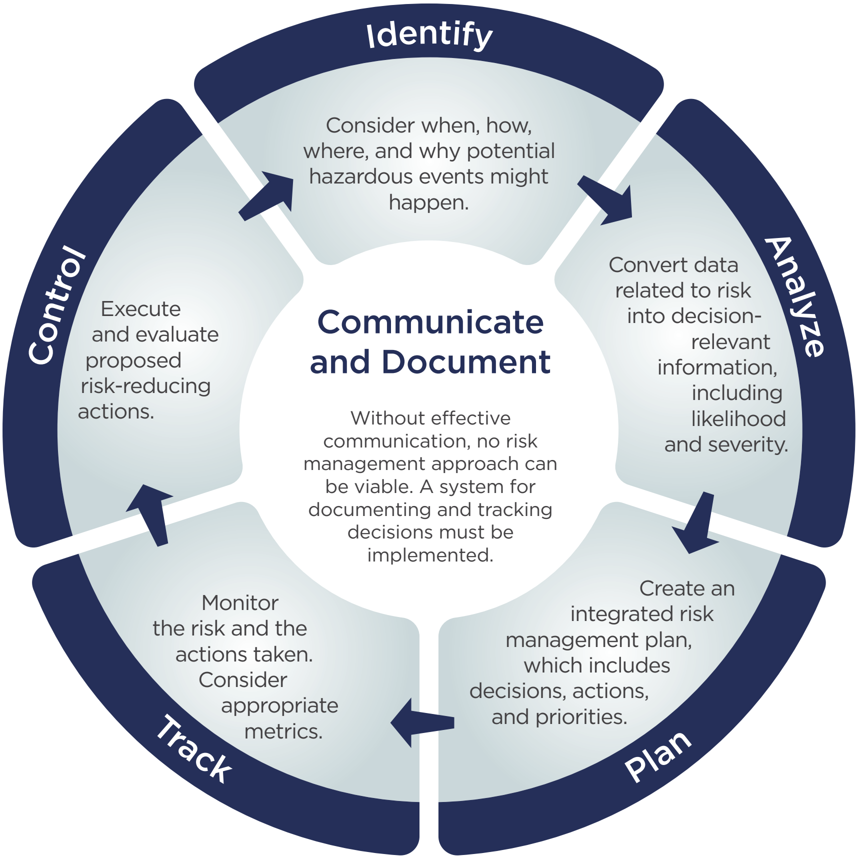
Uncertainty refers to the limitedness or absence of data and information to the extent that the probability and possible outcomes of hazardous events cannot be established conclusively. One approach to help reduce uncertainty is to include a wider evidentiary base.

Ambiguity refers to a situation in which different and sometimes divergent thinking or interpretations are applied to the same risk phenomenon. Ambiguity may be a function of legitimate differences in interpreting data among disciplines, but it may also be a function of differences in value judgments of what is tolerable with respect to a risk.

(Reviewed in Klinke & Renn, 2012)

Risk management can be an iterative and adaptive process

Research in decision theory recognizes that decisions about risk-reducing actions require communication and monitoring, which, in turn, can inform future risk assessments (Rausand, 2011). Continuous risk management is a formalized approach to connecting risk analysis, management, and communication in an iterative and adaptive process (Figure 2.2). As new information and knowledge arise, risk management can be updated and improved through multiple iterations of the management cycle. While such continuous risk management models are not yet a formalized part of the plant health system in Canada, they may be familiar as *adaptive management* approaches in the fields of environmental assessment (e.g., GC, 2019d) and wildlife conservation (e.g., Serrouya *et al.*, 2019).



Adapted from Rausand (2011)

Figure 2.2 Continuous Risk Management

Continuous risk management recognizes communication and documentation as central to the process, ensuring that future iterations of risk assessments are fully informed by past iterations, as well as by any new knowledge generated or identified by actors and participants since then.

The Panel considered plant health risks in the current Canadian system through a multidisciplinary lens following a continuous risk management model, examining aspects of the identification, analysis, planning, tracking, and control of current and emerging plant health risks. A notable gap in the Canadian plant health system is the absence of Indigenous knowledge systems in identifying and determining risks, and Indigenous experts and governments in decision-making processes (Chapter 6).

3

Environmental Risks to Plant Health

Chapter Findings

- Canada's climate is changing. Higher temperatures, more frequent and extreme weather events, and changing precipitation patterns can cause widespread plant damage that is difficult to predict and mitigate.
- Climate change, coupled with increasing land conversion, is altering the quality, availability, and connectivity of plant habitat, resulting in native biodiversity declines.
- Plant ecosystems are less resilient to environmental changes when soil health and pollination services decline.
- The rapid pace of environmental change challenges the ability of plant populations, as well as the plant health system itself, to adapt.
- Innovative management practices and technologies are promising practices to mitigate risk, but their current scope, development, and adoption pace may be inadequate to address future plant health needs.

While other threats exist, climate change, some land-use practices, and pests (discussed in Chapter 4) are the main drivers of environmental risks to plant health in Canada. Environmental threats are interconnected and often have cumulative and interrelated effects. For example, abiotic risks (such as rainfall) produced by the environment can directly and indirectly affect and amplify biotic risks (such as pest outbreaks), and vice versa (Seidl *et al.*, 2017). While plants always experience abiotic and biotic stress, climate change amplifies current stressors, increases uncertainty, and has the potential to introduce new risks.

This chapter examines how changes to the environment, particularly those driven by climate change and land-use practices, exacerbate existing plant health risks. Risk areas discussed include changes to abiotic conditions, soil and pollination threats, and declining habitat quality and availability. The result of these changes is greater uncertainty of the likelihood and impact of risks, which in turn complicates risk management. The plant health system in Canada is adapting to some of the environmental risks brought about by a changing climate, and some promising practices are highlighted throughout. Key regional and sectoral variations are also noted.

3.1 Changes to Abiotic Conditions

Plants need a suitable climate, including adequate moisture, to grow optimally. While shifts in abiotic conditions occur naturally, climate change (including higher temperatures, more frequent and severe extreme weather events, and changes in CO_2) is intensifying these variations. In turn, these changes to abiotic aspects of the environment can lead to widespread plant mortality, and the subsequent loss of their economic, ecological, and cultural functions.

3.1.1 Increasing Temperatures and Variability

The rise in temperature in Canada and globally is attributed to increased CO_2 emissions, which have almost doubled since 1750 (GC, 2019b; IPCC, 2021). While most of the country is warming, northern and western Canada have experienced especially strong warming trends (Vincent *et al.*, 2012). The average temperature across Canada is projected to increase by 1.5°C by 2050 compared to that measured between 1986 and 2005, and by 1.8°C by the end of the century if CO_2 emissions are not reduced[7] (GC, 2019b). If carbon emissions remain high, temperatures could increase by 2.3°C by 2050 and 6.3°C by 2100. Northern Canada is expected to warm by as much as 7.8°C by 2100 (GC, 2019b).

The impacts of increasing temperatures on agriculture are uncertain

Warmer summers in Canada are projected to make the growing season longer (GC, 2019b), which may provide farmers with more crop choices (Kulshreshtha, 2019), enable some crops to be grown farther north (GC, 2014a), and subsequently may generate GDP gains (Ochuodho & Lantz, 2015). Modelling suggests that warming of up to 3°C in Canada could increase wheat and canola yields in the next few decades (Qian *et al.*, 2019). However, the potential yield benefits decline after warming increases beyond 2.5°C (Qian *et al.*, 2019) given that, past a certain threshold, high temperatures can be harmful to crops (Hatfield & Prueger, 2015). This is consistent with other models that found short-term gains in wheat yield with a modest increase in temperatures, but long-term decreases if the climate warms 4°C on average (Asseng *et al.*, 2015).

Crucially, however, most modelling considers temperature increases in isolation. Extreme weather events — which will be more frequent and severe as a result of climate change — are rarely included in models (Smith *et al.*, 2013; Qian *et al.*, 2019). Nor do models often consider interaction effects among plants, or multiple disturbance agents (e.g., pests) (Seidl *et al.*, 2017; Boyd & Markandya, 2021). One

7 According to Canada's Changing Climate Report, a low-emission scenario would require global CO_2 emissions to "peak almost immediately and reduce to near [net] zero well before the end of the century" (GC, 2019b).

systematic review found that drier air associated with warming will reduce yield and plant growth, even in well-watered plants (López *et al.*, 2021). Thus, it is uncertain whether crop productivity will actually increase (Kulshreshtha & Wheaton, 2013).

Climate change will reduce the quantity and quality of Canada's timber supply

Climate change is expected to reduce the quantity and quality of timber supply among Canada's commercial tree species by 2 to 23% by the 2080s (NRTEE, 2011). This anticipated decline in productivity is due not only to changes in tree distribution and growth from higher temperatures, but also to extreme weather events and shifts in pest distributions (Williamson *et al.*, 2012; NRCan, 2020k) (Section 3.1.2 and Chapter 4, respectively). Models predict that, for most of Canada, 90 to 100% of total wood volume could be at risk of mortality given climate change conditions between 2071 and 2100 (Boucher *et al.*, 2018). These models include the negative impacts of droughts, wildfires, and pest outbreaks (Boucher *et al.*, 2018).

Box 3.1 Climate Change Impacts on Trembling Aspen

Trembling aspen (or white poplar) is the most abundant deciduous tree in Canada's boreal forest (NRCan, 2020c). The tree species is important economically (e.g., wood fibre) and ecologically (e.g., food and habitat for wildlife). However, this tree species is drought-sensitive. Severe droughts in recent years have resulted in widespread dieback and decline of trembling aspen in the Prairies (NRCan, 2020c).

The 2001 to 2002 drought alone caused a 20% higher mortality rate of trembling aspen, leading to 45 million tonnes of dead biomass in Alberta and Saskatchewan — the most acutely drought-affected regions (Michaelian *et al.,* 2011). This amount is equivalent to two years' worth of the total hardwood tree biomass harvested in Canada (NRCan, 2020c). In addition to drought, which was the biggest factor in aspen mortality, pest outbreaks facilitated by climate change have also contributed to its decline (Price *et al.,* 2013; Chen *et al.,* 2018).

The changing composition of forests due to climate change further threatens timber supply (Brecka *et al.*, 2018). For example, boreal forest composition is shifting towards more abundant deciduous species compared to conifers (Searle & Chen, 2017). While this shift is a natural response to changing conditions, and the forestry industry can use other species, most forest products are composed of coniferous trees (NRCan, 2020b), leading to potential timber supply reductions. Overall, trees that dominate the northern portion of Canada's boreal forest are the most vulnerable to climate change (NRCan, 2020c). Although there is a general shift to deciduous trees, these are also not immune to the effects of climate change, as illustrated by trembling aspen (*Populus tremuloides*) (Box 3.1).

Reductions in timber quantity and quality will result in financial losses. Climate change impacts on timber supply are estimated to cost between $2 and $17 billion per year by the 2050s, which would reduce Canada's GDP by 0.3% (NRTEE, 2011). Another estimate predicts that cumulative Canadian GDP losses by 2080 could be up to $459 billion if no adaptation actions occur (Ochuodho *et al.*, 2012). These impacts will not affect all regions in Canada equally. British Columbia's economy is forest-reliant, making it more vulnerable to timber supply-related losses (NRTEE, 2011).

3.1.2 Extreme Weather Events

Changes in climate, including increasing temperatures and shifting precipitation patterns, have made extreme weather events (e.g., droughts, floods, heatwaves, wildfires) more frequent and severe (IPCC, 2021). The likelihood, frequency, duration, and intensity of extreme events in Canada are projected to increase in the future (CCA, 2019b; GC, 2019b). Extreme heat events, in particular, will become more frequent (GC, 2014a). Extreme weather events already lead to tree and crop mortality in Canada and are expected to cause more widespread plant damage, with associated economic and ecological losses (GC, 2014a). These factors, coupled with significant regional differences in the type and occurrence of these events, introduce a higher degree of uncertainty into risk management in Canada's plant health system.

Precipitation in Canada is changing

Compared to changes in temperature, there is wider variability in model projections on atmospheric circulation affecting precipitation patterns, which results in greater uncertainty (Shepherd, 2014). Nevertheless, there is evidence showing that fluctuations in regional precipitation patterns are associated with increasing temperatures and changes in Canada's climate (GC, 2014a). While precipitation is expected to increase overall, changes will not be uniform across Canada and, in general, will not compensate for the projected decrease in soil moisture availability (Bonsal *et al.*, 2019). Northern Canada is projected to experience a disproportionally larger increase in precipitation; in contrast, southern Canada is projected to see less precipitation during the summer months (GC, 2019b). One region (e.g., the Prairies) may experience extreme droughts in the same year that another region (e.g., Ontario and Quebec) experiences extreme precipitation events (ECCC, 2017). In addition to average precipitation, the frequency of daily extreme precipitation events in Canada will increase in the future (GC, 2019b). Increasingly variable precipitation can lead to longer and more frequent droughts and extreme precipitation events, the latter possibly resulting in floods and physical damage to plants (GC, 2014a).

A lack of precipitation in some areas can lead to more frequent droughts, decreased crop productivity, and significant plant mortality

Droughts and soil moisture deficits are expected to become more severe and frequent in Canada and globally because of climate change (AAFC, 2020c; IPCC, 2021). The impacts of these extreme events are projected to be the most severe in the Prairies and interior British Columbia during the summer months (GC, 2019b; Gov. of SK, 2021a). Droughts can reduce crop yields by as much as 50% on average in a given region compared to normal growing conditions (AAFC, 2020c). The 2001 to 2002 and 2017 droughts exemplify the multiple risks and negative impacts on plant health associated with decreased precipitation (Box 3.2).

Box 3.2 Impacts of Drought Events on Canadian Agriculture

2001 to 2002: The 2001 to 2002 drought in Canada was one of the most severe in North America in over a century (Wheaton *et al.*, 2008). Saskatchewan and Alberta were particularly affected, but other regions where drought is less common (e.g., eastern Canada) were impacted as well. The higher-than-average temperatures and well-below-average precipitation levels enabled pest outbreaks, particularly grasshoppers (Powell *et al.*, 2007; Wheaton *et al.*, 2008). The drought also decreased crop productivity. Crop yields were below average, and agricultural production decreased by $3.6 billion during the drought years (AAFC, 2016). Several provinces experienced no net farm income or sustained a net loss during this period, which had not occurred in over 25 years (AAFC, 2016).

2017: Another severe drought occurred in 2017 in western Canada. Southern regions between the interior of British Columbia and the Prairies experienced the driest summer in over 70 years[8] (ECCC, 2017). Many areas recorded less than half their normal rainfall during the growing season (ECCC, 2017). Multiple crops were impacted, but canola was particularly hard hit. For example, in August 2017, only 28% of canola crops in southern Alberta were rated as in “good or excellent” condition compared to an average of 70% the previous year (Gov. of AB, 2017). Notably, farmers experienced less severe damage in some areas by using practices adapted for drier climates (Tait, 2017; Cherneski, 2018). Research and innovation, as well as monitoring and early-warning efforts, contributed to better drought management in 2017 (Cherneski, 2018).

Storms will become more severe in some regions, leading to forest damage

Wind is a natural disturbance agent in many forest ecosystems (NRCan, 2020k), but climate change can cause more severe winds, resulting in tree damage. While it is difficult to directly link climate change with wind speed changes (GC, 2019b), some models predict that, by the end of the century, wind gust events (i.e., brief rises in wind speed) will increase in frequency and severity across Canada (Cheng *et al.*, 2014). Another study projects increased wind damage in British Columbia’s coastal forests, where winds already pose a risk to trees (Haughian *et al.*, 2012).

8 This report was completed during the summer of 2021, prior to the conclusion of that year’s drought season.

While catastrophic windthrow events (i.e., trees uprooted by wind) are infrequent (Bouchard *et al.*, 2009), one study predicts a 3 to 30% increase in risk of windthrow due to soils staying unfrozen for months longer than usual as temperatures rise in eastern Canada (Saad *et al.*, 2017). Therefore, increased temperatures and windthrow events due to climate change pose risks to trees in Canada. There will likely be notable regional variations in these impacts, with trees in Atlantic Canada being at the highest risk of windthrow (Saad *et al.*, 2017). An increase in the frequency of extreme autumn storms (including hurricanes) has also been documented in Atlantic Canada (GC, 2019b). Hurricanes are included among the three most important disturbance agents in Nova Scotia's forests, such as Hurricane Juan in 2003, which led to over two million ha of forest damage in that province (Taylor *et al.*, 2020).

Extreme flooding will occur more often, affecting plants in unpredictable ways

Climate change has increased the likelihood of extreme flooding events in Canada (GC, 2014a). While it is difficult to attribute climate change to specific flood events, some event-attribution models have linked precipitation increases and climate change to specific events, such as the 2013 Alberta floods (Teufel *et al.*, 2017). Floods can have devastating effects on plants; for example, they can reduce crop yields by as much as 50% on average in a given region compared to average yields under normal conditions (Wang *et al.*, 2015; AAFC, 2020c). As sea levels rise, flooding is projected to increase in coastal regions of Canada (GC, 2019b). British Columbia is especially vulnerable, as coastal flooding can lead to the loss of farmland in the agriculturally productive Lower Mainland (BCAFCAI, 2013; GC, 2014a).

Climate change increases the risk of severe wildfires, leading to tree mortality

Forest fires are naturally occurring disturbances that contribute to the health and renewal of many forest ecosystems in Canada (NRCan, 2020k). However, as temperatures rise and increase the risk of heatwaves and drought, there will also be a corresponding increase in *fire weather* —conditions that favour the occurrence and influence the behaviour of forest fires, such as temperature, humidity, wind speed, and rainfall (CCA, 2019b; GC, 2019b; IPCC, 2021). More fire weather days are expected in certain regions, including British Columbia and Alberta (GC, 2019b). Under these conditions, widespread wildfires, such as the 2017 wildfire season in British Columbia (Box 3.3), will become more severe and occur more often. It is projected that the area of forest burned each year in Canada will double by 2050 and that, overall, there will be more extreme and unmanageable fires, leading to devastating environmental, economic, and social impacts (NRCan, 2020k).

Box 3.3 British Columbia Wildfires, 2017

The 2017 wildfire season was the most damaging in British Columbia's recorded history.[9] Wildfires burned an area of over 1.2 million ha, eight times larger than the historical average (Lions Gate Consulting Inc. *et al.*, 2018). A state of emergency lasted 70 days — the longest in the province's history at the time (Gov. of BC, 2020). The total fire suppression cost was $649 million, and 65,000 people were evacuated (Gov. of BC, 2020). While these forest ecosystems will likely recover, the impact on the forestry industry was significant. The wildfires burned the equivalent of one year's worth of timber harvest in the interior of British Columbia (Hunter, 2017), causing an average of 54% timber volume loss in the Cariboo Region, the most severely impacted area (BC MFLNRORD, 2018). Although the maximum volume of timber allowed for harvesting did not change immediately after the wildfires, timber supply in the medium term is expected to decline in the region (BC MFLNRORD, 2018). Forest biodiversity was also reduced, especially among species that depend on closed tree canopies (Nicholls & Ethier, 2018).

Climate change was directly associated with the 2017 wildfire season in British Columbia's interior. There were record warm and dry conditions that summer (Kirchmeier-Young *et al.*, 2019). An event-attribution analysis found that climate change considerably increased the likelihood of extreme high temperatures in the region, and the area burned was 7 to 11 times larger than what could be expected without climate change's influence (Kirchmeier-Young *et al.*, 2019). In addition to climate change, the accumulation of fuel due to the historical suppression of naturally occurring fires, and some forest management practices that do not prioritize resilience, also contributed to the severity of these wildfires (Abbott & Chapman, 2018; AGBC, 2018).

3.1.3 Water Availability

The availability of freshwater is vital for Canada's agricultural industry. Changes in water availability in some areas — such as the Prairies and the interior of British Columbia — may limit crop growth, and the ability to expand irrigated agriculture (GC, 2014a). Higher winter temperatures can decrease the accumulation of snow in alpine areas and across the Prairies, leading to a decline in annual stream flow and reduced water supply later in the growing season (Kulshreshtha, 2019). All of these factors contribute to less water availability for plants in these regions.

9 This report was completed during the summer of 2021, prior to the conclusion of that year's wildfire season.

In response to shifts in water availability, government reports on climate change adaptation have called for the need to revise and/or redevelop water management plans and policies, and make them more holistic (GC, 2014a). One adaptation action, for example, is capturing excess water for use during droughts (GC, 2014a). The storage of water is already practiced in some parts of Canada, including Delta, British Columbia, where cranberry (*Vaccinium macrocarpon*) growers store water for late-season use (BCAFCAI, 2013). This strategy may not be feasible for larger agricultural areas, however, so enhancing current irrigation infrastructure and monitoring its effectiveness are essential (BCAFCAI, 2013). Irrigation in Alberta relies on catchments replenished by excess water capture, but there are limited opportunities to expand the province's capacity (Gov. of AB, 2021a).

Increasing capacity and adapting existing irrigation infrastructure to manage water more efficiently may be helpful in mitigating future risks to agricultural plant health, as the current system may not meet increasing crop-water demand due to warmer climates and longer growing seasons (GC, 2014a). The Government of Saskatchewan recognized the importance of expanding irrigation capacity by investing $4 billion in a large-scale irrigation project in 2020 (Gov. of SK, 2020). The project will help diversify crop production and stimulate high-value crop growth (Gov. of SK, 2020). However, expanded irrigation infrastructure may put other plants at risk by reducing the supply of water in surrounding wetlands (ECCC, 2016), which support many threatened plant species (FPTGC, 2010). The 2021 federal budget included funding to create a new Canada Water Agency to help manage Canada's waters and support a more resilient irrigation infrastructure (GC, 2021a).

3.2 Risks to Soil Health

Soil is an essential consideration for plant health, as plants depend on it for physical, biological, and chemical support. Soil formation is a dynamic process that involves climate, topography, sediment, and rock type, as well as the organisms and vegetation that live on and within it (CSSS, 2020). Risks to soil health include erosion, organic matter decline, depletion of nutrients, low plant productivity, contamination, biodiversity loss, salinization, and desertification (AAFC, 2020b; Van Eerd *et al.*, 2021).

Plants depend on soil for growth, and in turn help to form and enrich soil. In addition to providing a physical substrate to support plant growth, soil is inextricably linked to plant health: it supports nutrient cycling and supply, water cycling and filtration, and habitat for diverse flora and fauna, while also helping to regulate climate (Hayat *et al.*, 2010; AAFC, 2020b; Van Eerd *et al.*, 2021). The organic portion of soil includes plant roots, fungi, microbes, and decaying matter (Simard & Austin, 2010). Some soil fungi, collectively termed mycorrhizal fungi, have reciprocal supporting relationships with plants (Simard & Austin, 2010). Decomposition of organic matter by soil fungi provides nutrients for plant growth (Frąc *et al.*, 2018). Networks of mycorrhizal fungi also facilitate the flow of water and nutrients (e.g., carbon, nitrogen) among plants, contributing to the growth, establishment, and survival of some species (Simard *et al.*, 2015). Plants contribute to soil formation through root growth (which can help to stabilize materials as well as help weather and break apart rocks), chemical reactions (e.g., releasing organic acids and carbon dioxide), microclimate creation (e.g., by reducing wind speeds), and by providing a source of carbon through organic matter (CSSS, 2020).

3.2.1 Soil Health's Role in Plant Health

Soil health is the "continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health" (Doran *et al.*, 1996). Soil health is vital to ensuring the ecological functions that contribute to plant health across all ecosystems, including agricultural and forest systems. Healthy agricultural soil produces food by providing the water, nutrients, and physical support required for crop growth (Norris *et al.*, 2020). Agriculture also depends on adjacent soils for ecological functions, such as water retention and purification, flood regulation, habitat provisioning, and carbon storage (Norris *et al.*, 2020). Similarly, healthy soils in forests produce biomass (e.g., trees), store carbon, bioremediate waste, regulate water quality and quantity, and promote biodiversity (Page-Dumroese *et al.*, 2021). The microbial community in soil supports plant growth, helps plants respond to stressors, and provides defence against pests (Trivedi *et al.*, 2020). A healthy soil microbiome also helps combat disease in plants; for example, Wei *et al.* (2019) found that the microbial community available to tomato plants (*Solanum lycopersicum*) influenced whether they stayed healthy or succumbed to *Ralstonia solanacearum*, a pathogen that causes bacterial wilt disease.

Risks to soil health are forces that have negative impacts on soil physical attributes (e.g., decreasing aggregate stability, increasing erosion susceptibility), chemical attributes (e.g., declining nutrients, increased salinity), and biological attributes (e.g., declining organic matter, loss of functional diversity). Certain management practices have lessened the risk to soil health decline over time in Canada. For example, soil erosion susceptibility decreased in the Prairies primarily because of reduced tillage (AAFC, 2021d). Other risks, however, continue to increase in some regions; land-use changes (e.g., shift from perennial crops to annual crops) in eastern Canada have led to lower levels of soil organic carbon (AAFC, 2021b). In all regions, climate change is a persisting risk to soil health because it impacts many factors that threaten soil. These factors include the frequency and severity of erosive events (Li & Fang, 2016); the soil-influenced conditions that regulate decomposition (NRCan, 2020d); plant productivity and the amount and type of carbon returned to the soil (Jansson & Hofmockel, 2020); biodiversity (Pugnaire *et al.*, 2019); and others involved in salinization or desertification processes (Sauchyn *et al.*, 2020).

Compaction threatens the physical attributes of soil

Many of the larger organisms that depend on soil, such as plants and earthworms that reciprocally create habitat for soil life, require that the soil be loose enough to grow roots or dig burrows (Meurer *et al.*, 2020). Soil compaction, which reduces the size of pore space, can limit the ability of soil to hold water and air, which are important for plant growth and function (Gov. of AB, 2010). Soil compaction also hinders the ability of plants to take up nutrients from the soil and can result in decreased crop production (Gov. of AB, 2010).

Soil compaction is a byproduct of agricultural operations, where heavy equipment is used for tilling, sowing, or harvesting products (Shah *et al.*, 2017). Compaction is particularly an issue if equipment is used when the soil is wet (Shah *et al.*, 2017). Soil compaction from forestry operations is also a key challenge to soil health (Batey, 2009). Forest soils are often loose and friable, with high porosity (Page-Dumroese *et al.*, 2021). As in farming, heavy equipment used to harvest trees compacts the soil, which also reduces water infiltration and water-holding capacity. Over the long term, forest soils may be particularly at risk of compaction, and recovery will depend on soil texture as well as the rate and severity of compaction during harvest operations. Compaction risk may be mitigated by minimizing the frequency and locations of heavy equipment entries during thinning operations, as well as considering seasonality and slope (Page-Dumroese *et al.*, 2021). As with farming, compaction is reduced when soils are dry, but unlike farming, forest harvest can be done during the winter to further minimize compaction (Reeves *et al.*, 2012).

Loss of organic matter in soil threatens its physical, chemical, and biological attributes, which impact plant growth

The availability of mineral nutrients in soil, as well as their concentration and combination, largely determine plant growth and development (Morgan & Connolly, 2013). Plants acquire some nutrients directly from soil, such as potassium and iron. Nitrogen and phosphorus uptake, however, requires a relationship with soil microorganisms that transform the nutrients into compounds that plants can access (Morgan & Connolly, 2013). Soil inputs, such as compost and fertilizers, are used in agriculture, gardening, and some forestry operations to increase nutrient availability for plant growth (Page-Dumroese *et al.*, 2021). The timing of the application of these inputs is important; for example, it can take two to three years to maximize the nutrient availability from composted manure (Brown, 2013). Additional decision points for producers in choosing soil amendments include type, material, concentration, and cost (Brown, 2013).

Maximizing the efficiency of soil inputs requires knowledge of the baseline soil conditions and the micro- and macronutrient demands of the crops being grown, as well as an ability to monitor and interpret the results of applications. Nutrient pollution is a potential ecosystem disservice created by the over-application of inputs. For example, a study of compost-based urban agriculture in Minnesota found that using urban compost (i.e., food, yard, and other municipal organic waste) in amounts scaled to meet the nitrogen demands of crops improved yields by 44% compared to a non-fertilized control (Shrestha *et al.*, 2020). However, the uptake of phosphorus in those crops was less than 10% of the magnitude of phosphorus in the compost. Phosphorus buildup in soil and subsequent leaching can in some cases negatively impact local water bodies, threatening aquatic ecosystem health. Therefore, optimizing the use of inputs to meet existing soil conditions and crop demands can help avoid ecosystem disservices (Shrestha *et al.*, 2020).

3.2.2 Improving Soil Health by Increasing Carbon Gains and Reducing Carbon Loss

Some agricultural and forestry activities can negatively affect soil health. There are, however, documented cultivation practices that minimize these impacts, including compaction reduction, conservation tillage (i.e., allowing build-up of crop residues on the soil surface), continuous plant cover, increasing plant and animal diversity, cover cropping (i.e., planting crops for soil cover rather than harvest), and organic amendments. These practices can help to maximize soil carbon gains and minimize soil carbon loss, leading to long-term improvements in the health of soil by influencing its physical, chemical, and biological attributes.

The community of microorganisms in soil depends on organic matter for nutrients and water retention, though there remain substantial gaps in our knowledge as to how changes in soil properties (e.g., through harvest, insect infestations, or fire) affect the function of these communities — and how that, in turn, impacts plant health. For example, the impacts of timber harvest operations on soil organic matter are variable; while harvest directly results in a loss of carbon (i.e., by removing trees), it can improve water availability and movement in soil, and increase temperature and light availability (Page-Dumroese *et al.*, 2021). These factors interact to influence soil and plant health in different ways depending on the site (Page-Dumroese *et al.*, 2021).

Different cropping systems and management practices have variable impacts on soil health, and research is ongoing to develop promising practices for a wide range of cultivation strategies, soil types, and climatic zones. For example, soil health is demonstrably improved by having continuous living plant cover, as healthy soils both provide for, and are sustained by, healthy plants and roots (e.g., Sokol *et al.*, 2019). While there are limited options for perennial cropping systems under Canadian growing conditions (Cattani & Asselin, 2017), planting winter cover crops has been found to increase agroecosystem stability and resilience (Van Eerd *et al.*, 2018).

No-till and reduced-tillage farming contribute to soil health improvements

Western Canada's cropping system historically relied on the extensive use of tillage to control weeds and prepare the seed bed (Thiessen Martens *et al.*, 2013; May *et al.*, 2020). This practice supported high yields, but also contributed to the loss of soil organic matter (Thiessen Martens *et al.*, 2013). In the Prairies, the resultant soil degradation led to concerns about crop production sustainability (May *et al.*, 2020). In the 1980s, multiple actors, convened by the (now defunct) Science Council of Canada, discussed ways to reduce soil erosion, salinity, and the loss of soil organic matter, which included long-term experiments and investment in strategic farming technologies (May *et al.*, 2020). No-till and reduced-tillage farming eventually became the main cropping system in the Prairies; 60% of total land in Canada prepared for seeding used no-till practices in 2016 (StatCan, 2021a).

No-till farming has improved soil health and crop productivity, and has facilitated diversified crop rotations (May *et al.*, 2020). Multiple factors enabled the adoption of no-till farming, including equipment innovation for seeding and fertilizer placement, research on promising practices for different regions and soil types, crop breeding, as well as the availability of herbicides. However, the no-till model of field cropping has also exacerbated selection for herbicide-tolerant weeds (May *et al.*, 2020), and increased the prevalence of residue-borne pests such as Fusarium head blight (Zhu *et al.*, 2019). There are also new concerns on the horizon, largely brought about by climate change and the intensification of production practices; identifying soil health threats are important to support the continued functioning of plant ecosystems.

3.3 Risks to Pollination Services

All sexual reproduction in plants relies on biotic (e.g., animals) or abiotic (e.g., wind, water) mechanisms for pollination (Bennett *et al.*, 2018). Pollination allows plants to make seed and reproduce.

3.3.1 Pollinators' Importance to Seed Production and Plant Reproduction

An estimated 78% of plant species in temperate-zone communities are pollinated by animals and insects (Ollerton *et al.*, 2011). Crops such as apples, blueberries, and alfalfa are entirely reliant on insect pollination for production (Reilly *et al.*, 2020). Pollination services can also improve productivity among crops that do not rely on insects. For example, canola is the second-largest field crop produced in Canada (by volume) and the largest crop contributor to GDP (StatCan, 2020a); while mostly wind-pollinated, up to 20% of canola crops in Canada depend on insect pollination (the majority of which is provided by honeybees) (Mukezangango & Page, 2017).

Seed production is limited by a lack of pollination services

Pollen limitation is a constraint on seed production caused by some lack in pollination services; it is measured by hand-pollinating plants and comparing their fruit and seed production to naturally pollinated plants (Bennett *et al.*, 2018). A study across the United States and part of Canada estimated between 64 to 94% of highbush blueberry (*Vaccinium corymbosum*), sweet cherry (*Prunus avium*), and tart cherry (*P. cerasus*) crops were pollinator-limited, and 100% of apple crops showed evidence of pollinator limitation (Reilly *et al.*, 2020). However, pollination limitation was crop-specific, with no evidence of limitation for almond (*P. dulcis*), watermelon (*Citrullus lanatus*), or pumpkin (*Cucurbita pepo*) (Reilly *et al.*, 2020). In this study, 74% of pollination services were provided by honeybees, with 26% provided by wild bees; however, the latter's importance varied by crop. Even within a crop type, the relative importance of honeybee versus wild bee pollination services can vary by geographic location. For example, fruit weight and seed set in highbush blueberry crops were explained primarily by honeybee abundance on bushes in Michigan, but primarily by wild bee abundance on bushes in British Columbia (Gibbs *et al.*, 2016). Temporal variation over multiple years or within season also complicates estimating trends in pollinator limitation (Thomson, 2019).

Declines in pollinator populations reduce the resilience of ecosystems

Insect pollinator populations are declining globally (Vanbergen & The Insect Pollinators Initiative, 2013), and in North America in particular (Potts *et al.*, 2010). Though there are limited data on the status of most wild pollinator populations and distributions, there are documented declines in pollinator occurrence and diversity in North America (IPBES, 2017). Dramatic declines in bumblebees (*Bombus* sp.) occurred in the early to mid-1990s in Canada and the United States, corresponding to an increase in multiple challenges to pollinator health including pathogen spillover from commercial honeybee colonies; the use of neonicotinoid pesticides, which started in North America in the early 1990s; and habitat loss due to intensification of agriculture and urbanization (Colla & Packer, 2008; Whitehorn *et al.*, 2012). In particular, pathogen spillover from commercial bumblebees used for greenhouse pollination in North America caused steep declines in some wild bumblebee species (Szabo *et al.*, 2012).

Not all pollinator species are declining, however. While half of bumblebee species examined in North America have declined since the early 1900s, the other half of species examined have stable or increasing populations, causing shifts in species assemblages (Colla *et al.*, 2012). The use of neonicotinoids has played a role in colony collapse disorder in honeybees (reviewed in Singla *et al.*, 2020) and decreased larval survival of monarch butterflies (*Danaus plexippus*) (Knight *et al.*, 2021). However, declines in many pollinator populations are also driven by land-use changes (e.g., urbanization), agricultural intensification, use of other pesticides, pollution, invasive species, pathogens, and a changing climate (Potts *et al.*, 2010; IPBES, 2017). Declines in pollinator diversity and abundance threaten the health of all plant populations (Ollerton, 2017). Fewer and less diverse wild bees can reduce the resilience of plant health systems, especially in the face of disturbances, leading to compounding impacts on ecosystem health (Mathiasson & Rehan, 2020).

Climate change is altering plant-pollinator relationships

If either plants or pollinators respond at a different rate to climate change-induced rising temperatures, mismatches can occur, impacting plants' ability to reproduce (Settele *et al.*, 2016). As well, the loss of blooms and fruits to frost damage impacts the pollinators and wildlife that have co-evolved with plants and depend on them for food and habitat (GC, 2014a). In a temperate forest in Illinois, warming temperatures and habitat fragmentation have caused mismatches between bees and flowering plants, as well as the loss of 50% of bee species in the area, leading to declines in pollination services (Burkle *et al.*, 2013). There is also evidence that the first-emergence date of wild bees in northeastern North America has advanced, on average, over 10 days since the 1970s, coinciding with rising temperatures (Bartomeus *et al.*, 2011). So far, the phenology of plants and wild bees has mostly shifted synchronously in response to climate change and has not resulted in severe biological disruption (Bartomeus *et al.*, 2011). However, Bartomeus *et al.* (2011) considered only common bee species (not those in decline). More consequential and more frequent mismatches are expected in the future if the climate continues to change rapidly (Bartomeus *et al.*, 2011; GC, 2014a).

3.3.2 Improving Pollination Services

Given pollinators' vital role in plant reproduction, practices that increase pollinator populations, such as habitat restoration, will benefit plant health.

Ecological restoration of pollinator habitat can increase the abundance and diversity of pollinator populations

The ecological restoration of habitat is a well-documented set of practices to address declines in pollinating species and pollen sources (Breland *et al.*, 2018; Sexton & Emery, 2020). Experiments in the United States showed that restoration actions (e.g., canopy thinning in woodlands) increase bee abundance and richness (Breland *et al.*, 2018). Meadow regeneration in southern Ontario also resulted in an increase in bee diversity and abundance for the first few years after the restoration project began (Rutgers-Kelly & Richards, 2013). Restoration projects on farms can be cost-effective. One study in California found that hedgerows — perennial plantings on field crop edges — not only enhance pollination but are also economically viable (Morandin *et al.*, 2016). If restoration projects are implemented, evidence suggests that having a range of pollen and nectar sources, and monitoring the effects of restoration projects (including whether pollination services actually increase), are important considerations (Colla, 2016; Breland *et al.*, 2018).

3.4 Habitat Quality and Availability

As habitats change, plants must shift their distributions, adapt to changing conditions, or face extirpation. Typically, plant populations have been able to adapt to changing environmental conditions; however, the increased rate and unpredictable nature of a changing climate, coupled with human activities — including land conversion and urbanization — have altered the availability and quality of habitat for plants, leaving many plant populations unable to adapt fast enough to grow optimally or survive.

Warmer climates and longer growing seasons in Canada may allow for better growing conditions for some tree populations (NRCan, 2020e), especially in the northern part of a species range (Lapointe-Garant *et al.*, 2010). For populations in the southern portion of the species range, however, warming may cause reduced growth due to drought and heat impacts (Lapointe-Garant *et al.*, 2010). Crucially, assumptions about plants successfully shifting their range farther north will depend on their ability to spread (which can vary by species) (Hampe, 2011), the presence of suitable soil (Section 3.2), and available habitat (Barber *et al.*, 2016).

3.4.1 The Impact of Shifting Climates and Habitat Availability on Plant Health

Climate change increases the risk of extinction for many plant species in Canada (FPTGC, 2010). Some rare plants (including globally threatened species) are particularly vulnerable due to their inability to migrate fast enough in response to increasing temperatures (Barber *et al.*, 2016). Longer-lived plants, including trees, are also at high risk due to the length of time they require to reach reproductive maturity (Aitken *et al.*, 2008). Tree populations are often unable to naturally migrate fast enough to shifting climate niches, leaving them maladapted (McKenney *et al.*, 2011; Gauthier *et al.*, 2014). The rate of climate change is projected to be 10 to 100 times faster than many tree populations' ability to naturally migrate to suitable areas in Canada (NRCan, 2020k). Arctic and alpine plant species will experience similar challenges (Charles & Stehlik, 2021).

Plant populations that migrate northwards to stay in their climate niche are also maladapted to the day length cues at these higher latitudes, predisposing them to growing at the wrong times of the year (Way & Montgomery, 2015). Plants that are not adapted to their local environments are more susceptible to pests and extreme weather events, resulting in reduced growth, and in some cases extinctions (Jump *et al.*, 2008). For example, trembling aspen, which are found in every province and territory in Canada (save Nunavut), is blooming weeks earlier in the year and becoming more vulnerable to frost damage (Beaubien & Hamann, 2011) (recall Box 3.1). Similarly, the warmer-than-usual March of 2012 in Ontario resulted in apple trees blooming earlier, consequently losing 80% of their fruit due to a severe frost later in the spring (Gov. of ON, 2019).

Northern and alpine plants are vulnerable as climate change decreases habitat availability

Ecosystems in northern Canada are especially vulnerable to distribution shifts (GC, 2014a); climate change is expected to contract the range of over 27 Arctic and alpine plant species (Alsos *et al.*, 2012). The polar willow (*Salix polaris*) is one of the few plant species that grows exclusively, or primarily, in northern latitudes, making it a notable example of a plant that is likely to experience a reduction in its ecological niche due to climate change (Prowse *et al.*, 2009). These northern species may also be at risk of increased competition and predation because, as populations migrate farther north, they start competing with local plants for resources and have the potential to introduce pathogens (GC, 2014a).

Northern Canada is already experiencing shifts in vegetation due to climate change altering environment suitability for various plant species. For example, shrub coverage has multiplied, and herbaceous species are increasingly growing on previously bare ground (Fraser *et al.*, 2011). Similarly, above-ground biomass (e.g., shrubs, forbs) and below-ground biomass (e.g., roots, rhizomes) have increased since the 1980s in tundra ecosystems; this is strongly correlated with higher temperatures in the region (Hill & Henry, 2011). This increase in vegetation, however, has not resulted in greater plant biodiversity (FPTGC, 2010). Northern plant biodiversity is expected to decline, at least in the short term (FPTGC, 2010), since warming benefits only a handful of northern plants (e.g., shrubs) that can outcompete other shade-intolerant species such as mosses (Walker *et al.*, 2006). Another key driver of change in northern Canada is the thawing of permafrost, which is accelerating with rising temperatures (Helbig *et al.*, 2016). Increased water-saturated conditions due to permafrost thaw has led to boreal forest loss, fragmentation, and overall forest structure modifications (Baltzer *et al.*, 2014; Helbig *et al.*, 2016). These changes to the boreal forest in turn affect climate systems and ecosystem services (Baltzer *et al.*, 2014; Helbig *et al.*, 2016). Wild foods, including berries and wild rice (*Zizania* sp.), are also declining in quality and quantity in northern Canada (GC, 2014a).

3.4.2 Land Use and Management Practices

The expansion of land use for agriculture and forestry, along with these sectors' enhanced productivity, has supported fibre and food availability for growing human populations. With new production practices and technologies, Canadian farms have also been able to grow more crop on less land (i.e., higher-intensity land use) (StatCan, 2017c). Land conversion, however, has contributed to habitat loss, which puts some native plant species at risk.

Land conversion increases the risk of extinction for many plant species

In Canada, there has been a shift towards increased urbanization. In 1901, approximately one-third of the population lived in urban areas, and this percentage increased to 84% by 2016 (StatCan, 2017b). Although Canada's built-up area represents 0.2% of the country's total land, a loss of natural land cover and green spaces, and increased habitat fragmentation, have been documented in and around southern population centres (Wang, 2018). Most urban areas in Canada are also located in some of the most productive biomes (SCAAF, 2018), suggesting some impact of urban sprawl on plant ecosystems and agricultural productivity. In the Montréal metropolitan region, for example, urbanization over a 45-year period has resulted in the loss of ecosystem services, including the loss of habitat that supports biodiversity and water provisioning (Dupras & Alam, 2015; Dupras *et al.*, 2016).

Rates of habitat loss in Canada are relatively small compared to other countries, but rates of biodiversity loss are equivalent (Coristine & Kerr, 2011). Since 1996, about 90% of habitat loss for at-risk terrestrial species in Canada is attributed to land conversion for agriculture, followed by urbanization (Kerr & Cihlar, 2003; Coristine & Kerr, 2011). There are higher levels of plant biodiversity in southern Canada than in northern Canada; yet, southern Canada has experienced higher levels of biodiversity loss, particularly in rare ecosystems such as oak savannahs (Coristine & Kerr, 2011). Even for species located primarily in highly urbanized regions of the country (e.g., southern Ontario), agriculture contributes more to habitat loss, as it occupies a larger portion of species' range relative to urbanized areas (Coristine & Kerr, 2011).

Habitat fragmentation exacerbates existing risks to plant health

Changes in land use can result in habitat fragmentation and less available habitat, both of which limit the ability of plant populations to migrate naturally through the landscape. In general, habitat loss and fragmentation interact with plant traits, making it more difficult for plants to disperse, persist, and establish themselves, resulting in decreased health (Zambrano *et al.*, 2019). Plant populations can more easily migrate (and thus establish in new areas as a means of adapting to a changing climate) in less fragmented landscapes (Barber *et al.*, 2016). Smaller, more isolated populations are more vulnerable to local extinction (Pardini *et al.*, 2017). With fewer individuals in a population, random fluctuations in mortality, growth, and recruitment rates have a higher probability of resulting in local extinction, while greater isolation reduces the chances of dispersers coming into an area and repopulating it. Moreover, less habitat provides fewer resources for individuals to grow and reproduce, leading to lower population growth rates irrespective of random fluctuations (Pardini *et al.*, 2017).

Climate change compounds the impacts associated with habitat fragmentation. Rare plants are especially vulnerable to climate change because they often grow in habitats that are already small or fragmented. This risk is more pronounced for rare northern plants, as habitat in alpine regions and cold steppes is expected to become more fragmented (and contract) as a direct result of climate change (GC, 2014a). The cumulative impacts of climate change and habitat fragmentation will limit the ability of many plant species to adapt (Coristine & Kerr, 2011; GC, 2014a), highlighting the need for increased landscape connectivity when managing ecosystems (Heller & Zavaleta, 2009).

Resource extraction activities can negatively impact forests

Human activities, including management practices and land-use decisions (e.g., resource extraction, urban development), can change forest ecosystems (StatCan, 2018). While not of the same magnitude as climate change, resource-based activities, such as timber harvesting, mining, oil and gas exploration and extraction, and hydro-electric production, can negatively affect Canada's forests (StatCan, 2018; NRCan, 2020k). For instance, access roads, well sites, dams, and reservoirs contribute to deforestation and habitat fragmentation, and facilitate the introduction and movement of invasive species when built through forested areas (StatCan, 2018).

Not all resource-based industries affect forests in the same way, however. The main deforestation drivers in Canada since 1991 have been conversion of forested land to agriculture, followed by mining, and oil and gas extraction (NRCan, 2020f). Urban expansion and the forestry industry also contribute to deforestation, but at smaller rates (NRCan, 2020f). Notably, however, less than 1% of Canada's total forested area has been converted to other land uses since 1991 (NRCan, 2020k). Canada's annual deforestation rate continues to decline, from 64,000 ha per year in 1991 to 34,300 ha in 2018 (NRCan, 2020k).

3.5 Risk Management in Light of Uncertainty and Change

Canada's plant health system has risk management strategies in place, including those that seek to maintain biodiversity in natural ecosystems, as well as to maximize productivity in agricultural systems and managed forests. However, existing management tools and tactics may become less effective in the future. There is a high level of uncertainty in terms of how climate change will affect the composition, structure, and functions of ecosystems (GC, 2014a). This, coupled with high levels of uncertainty about threats from biotic factors and habitat fragmentation, makes risk management increasingly challenging.

While there is extensive research assessing the impacts and vulnerabilities of plant systems in light of climate change, changes to management approaches continue to be limited (Keenan, 2015). In part, this is due to the challenge of considering long-term implications of management decisions, and accounting for uncertainty and unknowns (Keenan, 2015; Puettmann & Messier, 2019). However, a number of actors — including local farmers, foresters, governments, and Indigenous communities — have provided examples of approaches that can respond to risks in uncertain and unpredictable environments. In addition to current land management practices in place in many parts of Canada, there are promising practices in both forestry and agriculture that have been implemented on smaller scales and that may offer additional options to respond to climate change.

3.5.1 Forestry

Responsive management practices in light of the impacts of climate change will have long-term consequences for the forestry sector in particular, as trees have much longer growth cycles than agricultural crops (Williamson *et al.*, 2012). Forest managers in Canada are making some progress adapting to the impacts of climate change. For example, some managers have started to allow more low-intensity fires to burn in order to reduce fuel loads, and in turn reduce the risk of more severe wildfires (Williamson *et al.*, 2019). Although not commonly practised, forest management strategies have started to gradually shift away from planting large areas of a single tree species towards diversifying forest stands to make forests more resilient to pest outbreaks (Dymond *et al.*, 2014). Yet, these adaptation actions are in early stages, and are not widespread (Williamson *et al.*, 2019); there is still some resistance to modifying current forest management practices in Canada (Nelson *et al.*, 2016; Ameztegui *et al.*, 2018). Incentives may also differ depending on the type of land ownership in place. In British Columbia, for example, short-term forest leases can disincentivize licensees from undertaking long-term adaptation actions, even with government supports (Hotte *et al.*, 2016).

A systematic review of forest management recommendations to address climate change shows a focus on management based on current ecological patterns and processes (e.g., *adaptive* actions such as expanding forest reserves or removing invasive species) (Hagerman & Pelai, 2018). In contrast, there are few recommendations on how to manage forests using novel ecological patterns (e.g., *transformative* actions such as facilitating the establishment of trees outside of their natural ranges; Box 3.4) (Hagerman & Pelai, 2018). This trend is expected given the high level of uncertainty (Hagerman & Pelai, 2018; Puettmann & Messier, 2019). Managing for current biophysical patterns may be better understood, perceived as less risky, more socially and institutionally acceptable, and more economically viable than managing for transformative options (Hagerman & Pelai, 2018). Yet, a growing area of research on the anticipated impacts of climate change suggests that maintenance of current practices may not always be a feasible forest management goal (Stafford *et al.*, 2011; Messier *et al.*, 2015). For example, novel assemblages of species (i.e., novel ecosystems) have started to emerge (Seastedt *et al.*, 2008; Hobbs *et al.*, 2013). As climate and land-use changes make managing for maintenance untenable, Hagerman and Pelai (2018) argue that management strategies that consider multiple potential ecological futures will be critical.

Box 3.4 Assisted Migration of Trees

Assisted migration — the intentional translocation of species to areas outside their current native range — is an increasingly common climate change adaptation strategy for conservation of plant species (Heller & Zavaleta, 2009), including commercially important trees (Hagerman & Pelai, 2018). Assisted migration is being increasingly applied in forestry, particularly for species that may be unable to grow optimally as their local environments get drier and warmer (GC, 2014b). Most assisted migration actions and proposals have to date focused on intra-continental, single-species movements within or just beyond their native range (Pedlar *et al.*, 2012). For example, British Columbia was the first jurisdiction in Canada to implement an explicit policy to facilitate the movement of western larch (*Larix occidentalis*) seed from southern to northern regions of the province (Klenk, 2015).

While assisted migration has the potential to maintain forest productivity (Gray *et al.*, 2011), ecosystem services, and overall forest health (Kreyling *et al.*, 2011), it is not a universally accepted management strategy (Aubin *et al.*, 2011). Some concerns include the potential introduction of other risks (e.g., invasive species, pathogens), resulting in the disruption of recipient ecosystems (Hewitt *et al.*, 2011). There are also regulatory challenges, such as the absence of legislation and guidelines (Williams & Dumroese, 2013), and public opposition to assisted migration outside of trees' native range (Peterson St-Laurent *et al.*, 2018a). Nevertheless, assisted migration continues to be considered a plausible forest management tactic to help plants adapt to climate change (GC, 2014b), and professional foresters in Canada are increasingly in favour of adopting it (Peterson St-Laurent *et al.*, 2021).

The forestry sector has started to manage forests for multiple values and functions

Canada's forest management approach has historically prioritized a small number of commercially valuable species, and focused on a relatively narrow set of management objectives (Hagerman *et al.*, 2010; Messier *et al.*, 2015). For example, forest management practices have traditionally focused on optimizing timber production, thereby maximizing financial returns (Menzel *et al.*, 2012; Rico & Gonzalez, 2015). There are a few examples of multifunctional decision-support systems that take into consideration a broader definition of value, incorporating social, ecological, and economic components (Sheppard, 2005; Menzel *et al.*, 2012; Rico & Gonzalez, 2015). By providing more than one good or service from a given area of land — for instance, not only timber, but also wood-based bioenergy, climate change mitigation, water storage, recreational activities, and non-timber forest products — forests can be multifunctional, offering both economic and non-economic benefits (Mansuy, 2016). Messier *et al.* (2021) also show that there is increasing evidence for greater ecosystem service provision and resilience when planted forests are more diverse.

Most management tactics, however, have not changed in practice. Maximizing harvesting levels without adequately accounting for extreme risk events (e.g., wildfires, pest outbreaks) can also lead to the depletion of forest stock (Nelson & Scorah, 2021). Even if forests are managed for multiple values, Canada's current forest management approach does not capture the complexity of forest ecosystems, assumes it is possible to accurately predict which tree species will be desirable in the future, and inhibits forest resilience to disturbances (Messier *et al.*, 2019). New approaches may be needed (Box 3.5).

Box 3.5 An Approach to Forest Management That Emphasizes Functional Diversity and Redundancy

To date, most forest adaptation strategies consider climate change in isolation. Climate change adaptation is mostly based on introducing a limited number of new genotypes, species, or tree populations from different locations expected to be better suited to future climates (Hagerman & Pelai, 2018). Furthermore, these trees are often grown in monocultures for timber production (Dymond *et al.*, 2014). This is rooted in a forest management approach based on climate change predictability. In other words, it is a strategy to address a known risk. However, adaptation to other global changes, such as invasive pests and societal changes, has received less attention, in part due to the high unpredictability of such events (Puettmann & Messier, 2019).

An approach that considers adaptation to unknown risks is needed — one that emphasizes assemblages of tree species with high functional diversity (i.e., plant traits enabling a variety of responses to multiple disturbances) and redundancy (i.e., similar plant traits so that if one species is eliminated, community diversity of plant traits is maintained) (Messier *et al.*, 2015; Oliver *et al.*, 2015; Aubin *et al.*, 2016). A forest with high functional diversity is better able to withstand known and unknown disturbances, as it is composed of tree species with a wide range of response mechanisms. High functional redundancy also ensures the continuity of ecosystem functions if one species disappears. Multiple studies conducted in various ecosystems, including agricultural systems, show that adaptation and resilience are strongly linked to functional diversity (Mori *et al.*, 2013; Field & Parrott, 2017; Anderegg *et al.*, 2018; Frei *et al.*, 2020).

There are changes in forest management in Canada, in part because of a diversification of management actors. Forest biodiversity conservation and non-timber ecosystem services (e.g., carbon storage, clean air and water, recreation aesthetics) are increasingly areas of focus in management strategies (Messier *et al.*, 2015; Puettmann & Messier, 2019). While Indigenous Peoples in Canada have managed, used, and cared for forests for millennia (Chapter 6), provincial and territorial governments legally own the majority of Canadian forests, and have managed them in more recent centuries (primarily through leases to industry). The involvement of environmental groups and Indigenous people is increasingly recognized (albeit with ongoing limitations) in forest governance and management (Hagerman *et al.*, 2010; McGregor, 2011; Nikolakis & Nelson, 2015).

Monitoring indicators of change is vital for adaptation efforts, but capacity remains limited

The successful adaptation of forest management to environmental changes requires greater amounts of information, including indicators of change (Lorente *et al.*, 2020). Yet, there has been no comprehensive framework for reporting climate change impacts in Canada. To address this gap, the CFS established the Forest Change Tracking System in 2011 with the goal of informing the occurrence and scope of ongoing changes in Canada's forests (Lorente *et al.*, 2020). The list of well-documented indicators includes those related to drought, fire weather, growing season length, fire regimes, tree mortality, pests, and tree species distribution, among others (Lorente *et al.*, 2020). However, there is currently limited capacity to document additional indicators. These include other extreme weather events (e.g., lightning and thunderstorms), tree regeneration (e.g., success and failure of assisted migration blocks), phenology (e.g., budburst timing), and biodiversity (e.g., habitat, genetic diversity) (Lorente *et al.*, 2020). Addressing this gap is vital for future adaptation efforts in the forestry sector. Ground-level climate vulnerability assessments, which assist in the identification of risks, can strengthen Canada's adaptation capacity (Gov. of BC, 2021). Recognizing this need, the 2021 federal budget provides funding to undertake Canada's first-ever Census of the Environment to help monitor environmental trends (including ecosystems and species) (GC, 2021a).

3.5.2 Agriculture

Canada's agricultural sector is responding to the impacts of climate change by modifying farming practices and making use of crop varieties bred for specific traits such as drought tolerance.

Farmers are modifying their practices in response to climate change

While farmers have always faced weather uncertainty, climate change is making it more difficult to anticipate future conditions (GC, 2014a; CCA, 2019b). In an effort to maintain crop yields as temperatures rise, farmers are modifying their practices with adaptation and mitigation actions, including increased reliance on pesticides when faced with expanding insect populations, increased use of irrigation due to drought conditions, and changes in cropping systems (GC, 2014a; Deutsch *et al.*, 2018). Some adaptation actions documented in the Prairies include no-till or minimum-till farming, earlier seeding of crops, and crop sequencing within crop rotations (Cutforth *et al.*, 2007). The effectiveness of these strategies may be limited with more severe and unpredictable changes in climate (Kulshreshtha, 2019).

Breeding for specific traits is an adaptation tool

Crop breeding uses the genetic diversity found in plants to develop new cultivars with improved traits, such as higher yield, and biotic or abiotic stress tolerance (Swarup *et al.*, 2020). While multiple approaches to plant breeding exist, breeders often go through the following steps: (i) identify the traits of importance; (ii) find sources of genetic diversity for the desired traits; (iii) apply selection for the desired combination; and (iv) undergo the final testing requirements for variety development. There are many different selection techniques and varieties that can be produced depending on the crop type (Swarup *et al.*, 2020).

Different crop varieties, selected for specific traits that enable them to tolerate abiotic stressors, have been important for climate adaptation. For example, crops such as chickpea (*Cicer arietinum*) have been bred for early flowering to avoid damage from early-autumn frost events in the Prairies (Bueckert & Clarke, 2013). Drought-tolerant crop varieties have also been used for adapting agriculture to climate change (AAFC, 2020e). Drought tolerance can be achieved through breeding programs (Bueckert & Clarke, 2013) as well as through molecular tools.

Molecular tools that can improve breeding efficiency include genomic selection (Ontario Genomics, 2021), such as using molecular markers to increase crop yields or improve resistance to pests (Chen *et al.*, 2019). Molecular markers are linked to certain genes of interest in the plant genome, which then allow breeders to select for the presence of desirable traits early on in the breeding process rather than grow plants to maturity (Chen *et al.*, 2019). Recent advances in genomics have the potential to facilitate crop varieties that are resistant to frost, heat stress, and floods (Genome Canada, 2021; Ontario Genomics, 2021). Likewise, the field of epigenetics — the study of all the processes affecting the expression of genes (phenotypes) without altering DNA sequences (Amaral *et al.*, 2020) — offers prospects to allow plants to better respond to stressors and acclimate to changes in their habitats (Richards *et al.*, 2017).

Biotechnology can provide sources of genetic variation not available through traditional breeding techniques (Swarup *et al.*, 2020), facilitating, for example, the creation of crop varieties adapted to novel climate conditions. Transgenic breeding via genetic engineering has allowed for the targeted insertion of genes of interest into established varieties (Chen *et al.*, 2019). However, it can take more than a decade to develop new varieties, without considering additional time required for regulatory approval (Chen *et al.*, 2019). As of 2021, corn (*Zea mays*) is the only crop genetically modified for enhanced drought tolerance approved for use in Canada (CFIA, 2017a). Advances in genomic editing, such as the CRISPR/Cas system, have the potential to substantially decrease the time required to develop a new variety (Chen *et al.*, 2019). Societal challenges associated with the adoption of innovative breeding technologies, including regulatory barriers, public opposition, and inequitable access are further explored in Chapter 5.

Biodiverse systems and diversified crop rotations can help plants resist droughts

Biodiversity can improve the resilience of plant ecosystems. Agricultural practices that enhance or maintain biodiversity can also be important for adaptation to climate change (SCAAF, 2018). Biodiversity (measured as, for example, wildlife habitat on farmland) is one indicator of soil health (AAFC, 2020b), and can help agricultural ecosystems resist extreme weather events such as droughts (Nielsen *et al.*, 2015). Farms with diversified crops, for example, have more options if one crop fails (SCAAF, 2018).

A study in Ontario found that more diverse crop rotations improve yield stability during abnormally hot and dry weather, lowering the risk of crop failure (Gaudin *et al.*, 2015). More specifically, including wheat and red clover (*Trifolium pratense*) in rotation increased the yield stability of soybean by 16% in drought years. Yield benefits resulting from crop diversity were less pronounced in wet and cool weather (Gaudin *et al.*, 2015). Another study in North America found that corn grown as part of a more diverse rotation had lower yield losses during drought years (Bowles *et al.*, 2020). Annual revenue from rotating corn and soybean crops with wheat can also increase profit stability over time in Ontario (Janovicek *et al.*, 2021).

Genetic diversity is important to foster resilience

Plant genetic diversity is necessary to foster resilience and climate change adaptation efforts (IPBES, 2019a). Yet, plant genetic diversity is declining globally due to multiple factors, including urbanization, climate change, and the industrialization of agriculture through practices such as monocropping (Alsos *et al.*, 2012; IPBES, 2019a; ECCC, 2020d). While the genetic uniformity of crops is important for Canada's food supply, lower levels of genetic diversity hinder plants' ability to adapt to environmental and biotic stressors (Jump *et al.*, 2008; AAFC, 2018a). Most of the crops cultivated in Canada originated elsewhere, so crop traits of interest to Canada (i.e., traits adapted to changing conditions) are primarily located in cultivated and wild plant varieties in other countries (AAFC, 2018a; ECCC, 2020d). For example, less than 2% of global crop genetic resources are conserved in Canadian facilities, which highlights the need to strengthen international cooperation led by multiple actors, and further support gene banks (Owen *et al.*, 2014; AAFC, 2018a; McCouch *et al.*, 2020).

3.5.3 Natural Ecosystems

The establishment of protected areas[10] (PAs) across Canada has been the most common management approach to conserve biodiversity in various ecosystems. PAs have been important for plant conservation both in Canada and globally because they provide refuge to species and minimize human-induced stressors, including land-use changes and habitat fragmentation (CPCCCWG, 2013; ECCC, 2020a). However, there has been little progress in the discussion of how to adapt PAs to climate change in the last decade, which may limit their future effectiveness (Barr *et al.*, 2020).

Climate change threatens the effectiveness of protected areas

When PAs are managed effectively, they can conserve ecosystems, as well as the functions and services they provide (Lemieux *et al.*, 2011; ECCC, 2020a). However, as climate change alters habitat availability in various ecosystems, and as novel pests are introduced into PAs, fixed pieces of land may be a less effective conservation tool (Lemieux *et al.*, 2011). For example, changes in climate may alter available habitat, causing plant species to migrate outside of PAs (Hole *et al.*, 2009). As of 2019, 11% of Canada's terrestrial area and inland waters is formally protected, and the proportion of protected land has increased over time (ECCC, 2020a). However, this area remains below international biodiversity conservation targets to which Canada has committed (17% of land and inland waters protected

10 Protected areas include national, provincial and territorial parks; provincial and territorial forests and nature reserves; tribal parks; municipal preserves; and other lands set aside through public-private partnerships.

by 2020) (ECCC, 2019). Most large PAs in Canada are in the North (ECCC, 2020a), and therefore not all of the country's ecosystems are equally conserved.

While PAs continue to be a cost-effective means of conserving ecosystems and constitute an important climate adaptation tool (Dudley *et al.*, 2010; Lemieux *et al.*, 2011; CPCCCWG, 2013), PA management and governance approaches will need to adapt in order to remain relevant under climate change (Heller & Zavaleta, 2009). Integrating PAs into regional land-use planning, institutionalizing ecosystem-based management, and deliberately designing PAs for complexity, resilience, and redundancy can help ensure they conserve biodiversity and ecosystem functions (Lemieux *et al.*, 2011). More active management interventions within PAs (e.g., assisted migration) may also be necessary (Lemieux *et al.*, 2011). Initiatives aimed at maintaining or restoring landscape connectivity can help build resilience in PAs (Heller & Zavaleta, 2009). An ecosystem-based approach to adaptation that focuses on conserving ecosystem functions (rather than individual species) may be particularly suitable as a climate-change adaptation tool (CPCCCWG, 2013; GC, 2014b). Establishing PAs co-managed with Indigenous Peoples and local communities has also been shown to facilitate management of climate change risks (Lemieux *et al.*, 2011).

4

Pest Risks to Plant Health

Chapter Findings

- The risk of pest establishment is higher when introductions occur from similar climatic regions; as climate change creates more favourable conditions farther north, pest species adapted to conditions in the United States could move into Canada.
- Trade and domestic travel introduce both novel and established pests into new areas. Pests also arrive in Canada via migration and dispersal vectors (e.g., wind, water, animals).
- Pests adapt to their environment and no single mitigation strategy can continue to work indefinitely. As plants and their pests evolve, so too must the approaches and tools used to mitigate harm and sustain ecosystem function.
- Supporting diversity in plant life and ecosystem functions, as well as diversity in economic and management strategies, reduces the vulnerability of plant ecosystems to pests.

Human-mediated changes in land use, climate, and movement patterns can alter the threat that pests pose to plant health. These changes can alter the location, frequency, and intensity of insect outbreaks and weed growth, and help invasive species spread and establish. Several factors influence the risk of the establishment of a new pest population to plant health. These include the likelihood of introduction to a new ecosystem, the suitability of that ecosystem to the pest, and the ecosystem's vulnerability to pest damage and spread (Figure 4.1).

4.1 Introduction and Spread

Some pest species are native to Canada, and conflicts arise when favourable environmental conditions for population growth lead to economic and ecological damage beyond an acceptable threshold. Others arrive in Canada through the movement of goods — intentionally imported for agriculture or landscaping use, or unintentionally imported with soil, wood pallets, or other plant products. Still other pests are naturally occurring in, or imported into, the United States or other countries, and travel into Canada via wind, water, or animal vectors. Mitigation strategies will vary depending on the pathway of introduction, though in all cases, the suitability and vulnerability of Canadian plant ecosystems also influence the likelihood and severity of outcomes.

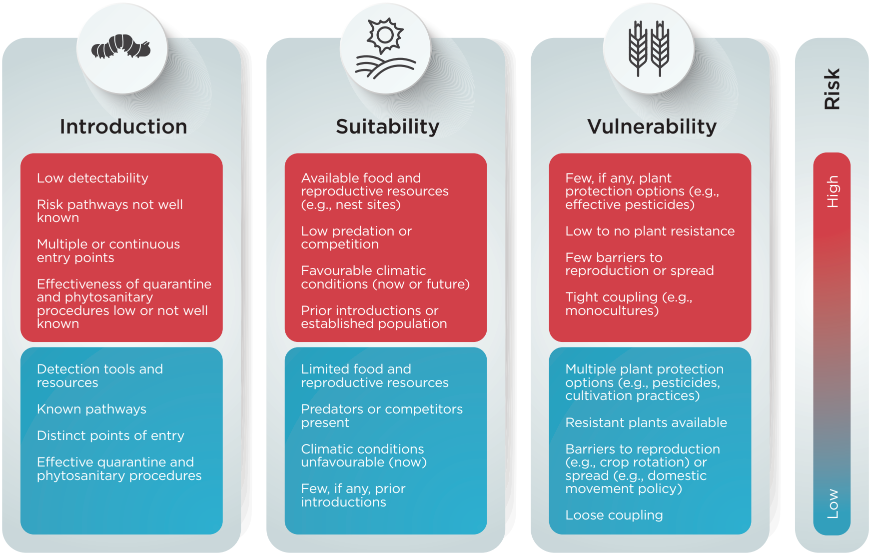


Figure 4.1 Factors Influencing Pest Risks to Plant Health

High-risk plant health scenarios involve pests that are largely undetectable (and uncontrolled) arriving via multiple pathways into areas with favourable environmental conditions (including ample food and reproductive resources), for which there are few, if any, protection or control options.

4.1.1 International Movements of People and Goods

Canada is part of an interconnected system in which people and goods are constantly traversing international borders. While globalization provides a multitude of benefits, it also contributes to an increase in risks to plant health. These risks are heightened through trade, travel, transport, and tourism (Waage & Mumford, 2008). The CFIA, in its *Invasive Plants Policy*, has identified major pathways by which the entry or spread of invasive plant species in Canada is regulated: seed (for propagation); plants for planting (e.g., ornamentals, soil stabilizers, medicinal plants); grain (e.g., animal feed, industrial uses, milling, crushing); hay, straw, packing material; and soil (CFIA, 2012). The *Invasive Plants Policy* applies to the importation and domestic movement of plants regulated as pests (under the *Plant Protection Act*) and those regulated as prohibited noxious weeds (under the *Seeds Act*); however, control measures are only applied to pathways deemed "feasible to regulate" (CFIA, 2012).

Wood from crates, pallets, and other packing materials has been identified as a high-risk material used in transporting goods (Campbell, 2001). The wood used in these products is typically of low quality, unsuitable for other uses, may already be damaged or infested by pests, or prone to infestation while left in the open awaiting use (Campbell, 2001). Standards for wood packaging imports into Canada (from any country other than the United States) include treatment requirements to reduce the spread of pests, as prescribed by federal regulation (CFIA policy directive D-98-08) or international standards (ISPM No. 15) (CFIA, 2008b).

Sea containers are also well-known vectors of pests, as hundreds of millions of containers are transported around the world annually (FAO, 2016). The most common contaminants on sea containers are soil and residue, which carry seeds, nematodes (i.e., roundworms), plant pathogens, and insects (Brockerhoff, 2016). Soil can be a particularly insidious vector. For example, four construction vehicles that were transported to the Rothera Research Station in Antarctica brought with them 132 kg of soil that contained intact grasses, mosses, and small plants, along with approximately 40,000 seeds, of which about 11% were demonstrated to be viable (i.e., capable of germinating under local environmental conditions), as well as spiders, midge and fly larvae, springtails, and mites not native to the continent (Hughes *et al.*, 2010).

In Canada, the five cities with the highest annual levels of forest insect-associated imports (as determined from import inspections) are the port cities of Montréal/Contrecoeur (Quebec), Vancouver (British Columbia), Fraser River (British Columbia), Halifax (Nova Scotia), and Hamilton (Ontario) (Yemshanov *et al.*, 2012). While the costs of preventative measures at such points of entry — including surveillance and sanitation — may be high, they are typically outweighed by the benefits, including saving on the very high costs of eradication strategies once a pest has been embedded in a non-native environment (Brockerhoff, 2016). For example, the Sea Container Hygiene System (SCHS), created in 2010, spans the Pacific Islands to New Zealand and Australia, and includes pre-export inspection, cleaning, and reporting (Brockerhoff, 2016; Gov. of Australia, 2019). The SCHS has been found to reduce contamination rates by 90% and has had economic benefits by lowering the need for additional treatments and measures once a product arrives at its destination (Brockerhoff, 2016; FAO, 2016).

In 2013, a draft International Standard for Phytosanitary Measures (ISPM) was written in order to minimize the impact that shipping containers have on ecological health (IPPC, 2013). Its measures include:

- visual examination of sea containers for contamination,
- methods to eliminate contamination,
- certification of shipping companies,
- verification of cleanliness (visual examination), and
- preventing contamination of clean containers (IPPC, 2013).

The draft ISPM also identifies guidelines for importing countries, including guidance on inspections for compliance and cooperation among national plant protection organizations (NPPOs) and shipping companies on improvement measures, research on preventing contamination, and information exchanges of inspection results (IPPC, 2013). While the risks posed by sea containers were recognized by the Commission on Phytosanitary Measures (CPM), and while it was agreed that the proposed ISPM would help address these risks, it was also noted that the ISPM would be "complex to achieve" and that the topic should be listed as "pending and reconsidered by the CPM in maximum five years" (FAO, 2020a). To date this ISPM has not been adopted.

Imported grain can be a pathway for weed seeds to spread in Canada

The importation of grain, whether for animal feed, human consumption, or industrial uses, is a risk pathway that can lead to the spread of weeds (via seeds) in Canada (Wilson *et al.*, 2016). Of particular concern is grain imported from areas with similar climates but different weed floras. Conversely, grain imported from areas with weed species that are also established in Canada are not considered to be as high of a concern. Farming practices in the country of origin, such as crop rotations, tillage, crop type, and herbicide use, as well as the timing, weather, and maturity of the crop at harvest, can affect the likelihood of weed seed presence in imported grain. Crops that are less competitive, grown organically, harvested close to the ground, or have small seeds are at higher risk for contamination by weed seeds than crops that are more competitive, treated with herbicides, harvested at greater height, and have large seeds. Grain handling (especially the cleaning and grading of grain) also affects weed seed contamination. All grain contains some proportion of allowable foreign material; variation in the composition of that foreign material, along with the practice of blending grains from different origins (to achieve a specific allowable level of foreign material) can lead to higher uncertainty with respect to the number and type of weed seeds in imports (Wilson *et al.*, 2016).

Cross contamination and spills during transport and storage can add to uncertainty of type and volume of weed seeds, and directly result in weed establishment and spread along roads, railroad tracks, and import facilities (Wilson *et al.*, 2016). Import requirements can include phytosanitary certification and import permits, as well as treatment requirements, such as heating grain to a certain temperature for a specific duration in order to reduce the viability of weed seeds. The end use of imported grain can also impact weed seed spread. Grain used for animal feed carries a higher risk of weed introduction and spread because of the minimal processing required and potential for spread to the local environment. Conversely, grain used for human consumption or industrial products carries a lower risk, as cleaning, processing, and end use reduces the risk of viable weed seeds escaping into the environment. Byproducts of grain cleaning are also used as a component of livestock feed; however, grinding and processing can reduce weed seed viability and mitigate the risk of spread from these products (Wilson *et al.*, 2016).

Many pest species arrive as imports for ornamental horticulture and landscaping use

Among the most dangerous imports are live plants destined for horticulture, which have been described as "a uniquely efficient pest introduction pathway" (Regelbrugge, 1998 as cited in Campbell, 2001). The reasons for this are two-fold. First, the horticultural industry is predicated on the sale of non-native species (Hulme *et al.*, 2017). For example, in the United States, non-native species account for 80% of nursery stock, and 90% of sales (Hulme *et al.*, 2017). For consumers, the decision to purchase non-native species is based on a preference for something unique; most consumers are also unaware of the potential environmental impacts of introducing non-native plant species into an ecosystem (Box 4.1). Second, there is a lack of regulation within the horticultural industry itself. It is difficult to control due to the number of actors involved, such as importers, nurseries, and consumers, among others. Because of this, compliance measures are challenging to implement and regulate (Hulme *et al.*, 2017).

Opportunities for regulation and policy options to discourage the importation of non-native plants for ornamental horticulture occur across the supply chain, from import and sales bans to voluntary codes of conduct and consumer awareness campaigns (Hulme *et al.*, 2017). For example, the Ontario Invasive Plant Council publishes *Grow Me Instead* guides to native plant alternatives for common, but invasive, horticultural plants (OIPC, 2020). Invasive plants are also assessed using the same risk analysis procedures as other pests regulated by the CFIA. There are currently 25 plants listed as regulated pests, along with 85 arthropods, 63 viruses, 39 fungi, 19 bacteria, and 8 each of nematodes, molluscs (all snails), and "unknowns" (unidentified agents of known plant diseases) whose movements are prohibited into and within Canada (CFIA, 2020c).

Box 4.1 Environmental and Health Impacts of Imported Plants

Both wild parsnip and European buckthorn were likely introduced to North America as horticultural products, with European settlers growing parsnip for consumption (Averill & DiTommaso, 2007), and later using buckthorn extensively as a landscaping plant in hedges and as windbreaks (Anderson, 2012b). Buckthorn and wild parsnip are among the top five invasive species of concern — along with common reed, emerald ash borer (*Agrilus planipennis*), and Japanese knotweed (*Reynoutria japonica*) — as reported by municipalities and conservation authorities in Ontario in 2019 (Vyn, 2019).

Parsnip was introduced to North America in the 1600s as a cultivated variety (*Pastinaca sativa* ssp. *sativa*), which likely escaped cultivation shortly thereafter and reverted to the wild form (Averill & DiTommaso, 2007). The wild form contains furanocoumarin, a chemical that deters predation, but also causes phytophotodermatitis in humans and livestock — a chemical burn that results when skin, sap, and sunlight combine (Averill & DiTommaso, 2007). Efforts to control wild parsnip — as well as the related giant hogweed (*Heracleum mantegazzianum*), another escapee from ornamental horticulture — are largely driven by concerns over human and livestock health; wild parsnip grows in fields, along roadsides, and in other publicly accessible areas (Page *et al.*, 2006; Averill & DiTommaso, 2007).

European buckthorn — planted in North America since the early 1900s — degrades wildlife habitat and reduces biodiversity through competition with native plants. It is shade- and drought-tolerant, spreads quickly because the fruits have a laxative effect on wildlife, and grows in dense thickets that outcompete native trees and shrubs (Anderson, 2012b). Buckthorn also causes harm to agricultural crops, as it can host pests such as oat crown rust (*Puccinia coronate* f.sp. *avenae*) and soybean aphid (*Aphis glycines*) (Anderson, 2012b).

E-commerce creates novel pathways for the introduction of non-native species

The growth of e-commerce has increased the potential for the trade and sale of invasive plants, seeds, and insects, and augmented the risk to Canada's agricultural crops, forests, and biodiversity (FAO, 2017a; CFIA, 2018a). While the same requirements facing the sale and transport of plants and plant products applied to traditional commerce also apply to e-commerce, the latter has, in many ways, proven more difficult to monitor, especially in light of the rapid expansion of trade in agricultural goods within this new marketplace (FAO, 2017a). An online marketing strategy that targeted North American consumers in 2020 revealed the scope of the online seed industry and the lack of regulation (Box 4.2). Unlike food products sold for consumption, seeds risk establishing and spreading invasive pests in new environments (FAO, 2017a).

Box 4.2 The Case of the Mystery Seeds

In 2020, people across North America began reporting the receipt of packages they did not order, which contained mysterious, unlabelled seeds. Responding to the issue, the CFIA (and the U.S. Department of Agriculture) asked the public to report these packages to regional offices, and to refrain from planting, composting, or throwing the seeds directly into the garbage where they could potentially sprout (CFIA, 2020a; Koebler, 2020; Lowrie, 2020). Most of the packages originated in China and, fortunately, the seeds were not generally from invasive or dangerous species (Lowrie, 2020). U.S. authorities determined that the seeds were part of a "brushing scam," in which online retailers generate fake orders by sending unsolicited packages to consumers, which allows those retailers to write fake reviews to bolster the product's online reputation. This finding alleviated concerns that the seeds were part of a broader bioterrorist threat (Lowrie, 2020). In response to the incident and subsequent investigation, Amazon — one of the world's largest online retailers — announced in September 2020 that it would ban the online sale of foreign seeds to U.S. buyers; however, there has been no information on whether the ban will be extended to Canada or any other countries (Ermont & Newman, 2020).

Unintentional importation of pests through contaminated mail and packages is recognized as a potential pathway for introduction, though it is not well documented or monitored (Meurisse *et al.*, 2019). Meurisse *et al.* (2019) considered this pathway to be similar in character to that of movements with personal baggage and food items. An analysis of inspections of baggage entering the United States from 1984 to 2000 revealed that 83% of pests found were associated with fresh plant material (e.g., cut flowers, fruit, plant parts), with relatively few hitchhiking without any associated plant material (6%) and fewer still associated with wood products (3%) (McCullough *et al.*, 2006).

4.1.2 Movement of People and Goods Within Canada

Travel and trade within Canada also contribute to the spread of pest species. Biosecurity guidelines for crop production can help reduce the potential for pest introductions on farms (e.g., Gov. of MB, n.d.), and campground policies and public education campaigns aim to reduce the movement of firewood and slow the spread of invasive forest pests (e.g., Gagné *et al.*, 2017). Apart from these, there is little regulation of domestic movement within Canada when it comes to protecting plant health, and most biosecurity protocols rely on voluntary actions by farmers, landowners, and tourists.

Road infrastructure facilitates the spread of invasive species in Canada

Large roads with wide shoulders and ditches create habitat with few competitors; high traffic volumes help disperse seeds; and road maintenance creates regular disturbances to the soil — all of these contribute to roads acting as habitat and dispersal corridors for invasive species (Joly *et al.*, 2011). For example, an exotic genotype of the common reed was introduced in North America in the early 1900s, and by the 1970s had begun to rapidly expand and dominate common reed populations (Lelong *et al.*, 2007). Negative impacts of the exotic common reed on native wildlife are well documented, including habitat loss for toads (Greenberg & Green, 2013), turtles (Markle & Chow-Fraser, 2018), and birds (Tozer & Beck, 2010), as well as substantial losses in plant biodiversity and species richness in wetland habitats (Meyerson *et al.*, 2000; Ailstock *et al.*, 2001; Silliman & Bertness, 2004). The exotic genotype now accounts for more than 95% of the common reed colonies in Quebec; its abrupt rise follows closely with the expansion of the highway network in that province between 1964 and 1979, and it appears to have a competitive advantage in the types of wetland habitat found in roadside ditches (i.e., low water, higher sodium levels from road salt applications) (Lelong *et al.*, 2007). Roads also account for much of the spread of common ragweed (*Ambrosia artemisiifolia*) in Quebec (Joly *et al.*, 2011), as well as the spread of noxious weeds in forest habitats (e.g., Birdsall *et al.*, 2012).

Domestic travel facilitates the spread of invasive pests in Canada

When a pest species is introduced into Canada through international trade, range expansion and establishment can be facilitated beyond its natural dispersal capacity by human-mediated movements between the point of entry (e.g., a port or border crossing) and previously uninfested locations (Koch & Smith, 2010). For example, the unintentional movement of eggs and other life stages that hitchhike on vehicles and goods is the primary mechanism for the spread of the LD moth[11] (*Lymantria dispar*) in North America (Box 4.3). In the Yukon, white sweet clover (*Melilotus albus*) has spread from roadsides — where it was likely introduced by contaminated heavy equipment used to clear highway rights-of-way — to riverbanks, where it causes changes to vegetation structure, increases fire frequency and intensity, and appears to reduce habitat for small birds (Snyder & Anions, 2008). At a smaller scale, recreational vehicles, bicycles, runners, and pedestrians moving through different areas throughout a day can feasibly contribute to the local spread of pest species (Anthony, 2017). While the impact of clothing or vehicle-mediated dispersal on species distributions relative to other vectors is not known, studies have demonstrated the ability of seeds to be transported by tourists on clothing, vehicles, and horses (Pickering & Mount, 2010). Approximately 15% of noxious weeds in the United States are transported on cars (Ansong & Pickering, 2013). While many pests may already be widespread in areas of high human density, of concern is the unintentional introduction of pests into relatively pristine areas through, for example, ecotourism (Pickering & Mount, 2010) or resource extraction (Snyder & Anions, 2008).

11 Also known by the common name "gypsy moth."

Box 4.3 LD Moths Hitch Rides Around North America

LD moths first arrived in Massachusetts in 1869, brought in by a French mathematician and astronomer hoping to cross the LD moth with a native silkworm, *Antheraea polyphemus*, in order to create a silk industry in North America (McManus & Csóka, 2007). Within 20 years, the moth had established itself to the point where defoliation was extensive and caterpillars were numerous enough to attract public attention, leading to control efforts spread over 250,000 ha, covering 30 towns and cities. These efforts were successful — few moths were found, and defoliation was minimal — so controls stopped in 1899. By 1905, however, LD moth populations had rebounded and spread to nearby states (McManus & Csóka, 2007).

To find food, LD moth caterpillars climb up and suspend themselves from the branches of trees on silken threads, where they catch the wind and can be carried upwards of a kilometre (Marshall, 1981). In 1906, it was recognized that the rapid spread of the moth over much larger distances was because egg masses and other life stages were being carried by vehicles along major roadways (McManus & Csóka, 2007). Control efforts were extensive and widespread, including the enactment of regulations, as well as chemical and mechanical eradications of infestations. However, new introductions were also occurring and, while control efforts reduced the rate of spread between 1916 and 1965, the rate increased by nearly ten-fold over the next three decades due, in part, to the development of a national highway system and the correlated rise in transportation in the 1970s (McManus & Csóka, 2007).

LD moths were first detected in Ontario in 1969, and they are now found anywhere there are oak trees (*Quercus* sp.) in that province (Gov. of ON, 2020b). They also consume maple (*Acer* sp.), aspen (*Populus* sp.), willow (*Salix* sp.), and other broadleaf trees, and there is evidence of LD moth defoliation in conifer species, including eastern white pine (*Pinus strobus*) (Gov. of ON, 2020b). LD moth populations are eruptive, occurring at low densities for several years before rapidly expanding into an outbreak phase that can last one to three years (McManus & Csóka, 2007). Most recently, LD moth defoliation increased from approximately 47,000 ha in Ontario in 2019 to more than 580,000 ha in 2020 (Gov. of ON, 2020b).

Forest pest species can spread through the movement of infested firewood

In a scenario modelling the movement of infested firewood, it was predicted that an initial pest outbreak in the Greater Toronto Area could lead to the infestation of all campgrounds in Manitoba, Ontario, and Quebec within two decades (Jentsch *et al.*, 2020). Indeed, the emerald ash borer followed such an invasion timescale after its introduction into Canada in 2002 (Jentsch *et al.*, 2020). Imported firewood may be heat-treated, kiln-sterilized, debarked, or chipped to kill pests, and big-box stores carry firewood from large-scale producers that heat-treat their wood (Gagné *et al.*, 2017). However, most campgrounds source their firewood from local providers, and campers themselves may source firewood from anywhere, including gas stations or other independent vendors. While there is some federal regulation restricting the movement of firewood into national parks and prohibiting movement from regulated pest areas to non-regulated areas, most enforcement is voluntary. Firewood disposal bins are placed at some international and provincial borders in Alberta, Manitoba, and Ontario, to encourage the voluntary disposal of potentially infested or infected wood prior to entry into the new province or country along heavily travelled routes. Provincial parks discourage the transportation of firewood into campgrounds by providing firewood for purchase, or by including firewood as part of the visitor camping fee, as do some private campgrounds. Outreach campaigns have used messaging such as "buy it where you burn it" and "don't move firewood" to inform the public of the risks of moving firewood (Gagné *et al.*, 2017). However, most efforts have been largely ineffective at stopping the spread of invasive species through firewood, and may continue to be relatively ineffective without long-term, large-scale, enforceable quarantines (Jentsch *et al.*, 2020).

4.1.3 Natural Pathways and Vectors of Spread

While Canada's border with the United States is a political barrier to the movement of people and goods between the two countries, pests may travel freely on the wind, in water, or through animal vectors across this divide. Similarly, provincial and territorial borders do not reflect physical barriers to movements for many pest species, though geographic features such as the Rocky Mountains and the St. Lawrence River can limit the movement of dispersers.

Not all pests depend on human-mediated pathways of introduction

Some pest species arrive in Canada on wind currents. For example, soybean rust arrived in North America via spores carried by hurricanes across the Atlantic Ocean from Africa (Fetch *et al.*, 2011), while other rust diseases (caused by *Puccinia* fungi) overwinter in the southern United States and migrate into Canada on wind currents, known as the "Puccinia pathway" (Fetch *et al.*, 2011) (Figure 4.2).

Reproduced with permission from Aboukhaddour *et al.* (2020)

Figure 4.2 Pathways for Typical Cereal Rust Migration via Wind

Wheat stem and leaf rusts overwinter in the southern-central United States and migrate north into Canada on winds via the Puccinia pathway. Since 2000, wheat stripe rust has been moving northward along the Pacific Northwest pathway following adaptation to higher temperatures.

Animals can also act as vectors of long-distance dispersal for pests. The seeds of invasive plants can be dispersed long distances when animals, such as birds and deer, consume their fruits and defecate viable seeds elsewhere on the landscape (Myers *et al.*, 2004; Bartuszevige & Gorchov, 2006). For example, American robins (*Turdus migratorius*) have been found to transport the seeds of the invasive Asian honeysuckle (*Lonicera maackii*) along fencerows and the edges of woodlots across eastern North America (Bartuszevige & Gorchov, 2006). Seeds and other reproductive plant material can travel by water, and high-water events can disperse the shoots and rhizomes of invasive plants throughout floodplains —

as is the case for Japanese knotweed — making controlling the spread of some invasive species particularly challenging (Colleran & Goodall, 2014).

Pest dispersal pathways can be complex and interact in unexpected ways

Oat crown rust is "arguably the most important disease of oat in Canada" (Fetch *et al.*, 2011). It causes yield losses in Quebec, Ontario, Manitoba, and eastern Saskatchewan. Unlike other crops affected by rust diseases, resistant oat cultivars have been difficult to establish, as oat crown rust has a secondary host (European buckthorn) on which sexual reproduction occurs; this accelerates genetic recombination of the rust and thus adaptation to resistance. Wheat rusts also have a secondary sexual host, barberry (*Berberis* sp.), and control efforts have included the largely successful elimination of ornamental barberry from susceptible areas (Fetch *et al.*, 2011). Buckthorn, however, has been much more difficult to control, and its spread is facilitated through seed dispersal by birds and other animals (Heimpel *et al.*, 2010). Ongoing spread and establishment of buckthorn are further facilitated by another invasive species, the emerald ash borer, which, by killing ash trees (*Fraxinus* sp.), creates forest canopy gaps that buckthorn exploits by outcompeting native trees and shrubs (Baron & Rubin, 2020).

There are further layers of ecological complexity in the interactions among agricultural pests, invasive species, and natural dispersal pathways. For instance, buckthorn is also host to the soybean aphid, which, in turn, may be an important food source for Asian ladybeetles (*Harmonia axyridis*) (Heimpel *et al.*, 2010). While the Asian ladybeetle is used as a biological control agent for other agricultural pests, its generalist feeding behaviour has led to impacts on non-target native arthropod populations; it is now considered a pest in fruit production, particularly for wine grapes (Koch & Galvan, 2007). The challenge of controlling natural pathways of dispersal and the complex interactions among species along those pathways — as evidenced here — point to the importance of strategies that reduce the suitability and vulnerability of ecosystems to these pests, such as support for invasive species management, and research and development of resistant cultivars (e.g., Fetch *et al.*, 2011).

4.2 Establishment and Population Growth

In order to establish themselves in new areas, introduced pests require habitat (Hall *et al.*, 1997). In some areas, climate change will increase the amount of available habitat for pest species; for example, as temperatures rise, insect larvae may be able to survive in larger numbers, leading to higher population growth rates (Bentz *et al.*, 2010). Previously unsuitable areas can quickly become hospitable as insect populations adapt to other environmental changes as well (Sambaraju *et al.*, 2012).

4.2.1 Forest Pests

Forest pest populations evolve under the combined pressures of climate change, changes in the intensity of land use and forestry practices, and ongoing introductions and range expansions of non-native species. For example, native tree pathogens may be relatively ubiquitous across a species' range, and outbreaks of disease may be linked more to environmental changes that increase susceptibility (e.g., drought, storm damage) than to the presence of the pathogen itself (NRCan, 2018). Management practices in mature forests (e.g., thinning) must therefore consider how climate change may interact with native pests when adopting methods to reduce the likelihood and severity of disease outbreaks (e.g., Wyka *et al.*, 2018).

Environmental stressors can exacerbate the severity of forest insect outbreaks

Native forest pest populations are expanding under changing climatic conditions (Box 4.4). The eastern spruce budworm (*Choristoneura fumiferana*) is a moth native to Canada's boreal forest that feeds mainly on balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*). Outbreaks of eastern spruce budworm occur every 30 to 40 years, last several years, and can severely defoliate tens of millions of hectares of trees (NRCan, 2020j). The most recent outbreak began in 2006 in Quebec and has led to moderate to severe defoliation in more than 7 million ha of forest as of 2017 (NRCan, 2020j). Warm spring temperatures and increases in cone production were associated with increasing synchrony among spruce budworm outbreaks across a 62.5 million ha area in Quebec over 28 years (Bouchard *et al.*, 2018). In 2018, an ongoing outbreak of the native jack pine budworm (*Choristoneura pinus pinus*) caused damage to more than 625,000 ha of forest around the Red Lake region of northern Ontario (OMNRF, 2020).

Box 4.4 Mountain Pine Beetle Range Expansion Under Climate Change

Mountain pine beetle (*Dendroctonus ponderosae*) is a species native to western North America that has affected more than 18 million ha of pine forest in an outbreak that began in the early 1990s and continues to this day (NRCan, 2019b). Mountain pine beetle has attacked half of the commercial lodgepole pine (*Pinus contorta*) in British Columbia and, as of 2017, has moved beyond its historic range in northern British Columbia into the boreal forest of Alberta (NRCan, 2019b). Climate change alters pine forest susceptibility to beetle outbreaks by influencing beetle population dynamics (e.g., development, reproduction, survival), synchronizing populations across a landscape (leading to larger outbreaks and range expansions), and influencing the susceptibility of host trees (Sambaraju & Goodsman, 2021). Most pine species in North America are suitable hosts, and an observed host shift to jack pine (*P. banksiana*) in Alberta has increased the risk of invasion by the beetle across the boreal forest (Sambaraju & Goodsman, 2021). Further, while the most recent available information shows that beetle infestations have not reached the Yukon (Gov. of YT, 2021), they have the potential to move northward into that territory, where tree populations lack evolved defences (Sambaraju *et al.*, 2012).

For deciduous trees such as aspen, oak, and maple, the forest tent caterpillar (*Malacosoma disstria*) can cause substantial defoliation during outbreak years (NRCan, 2019a). Widespread outbreaks of forest tent caterpillar — a native species — have been noted in the boreal forest since the 1930s (NRCan, 2019a), with the latest disturbance peaking in 2013 and affecting more than 7 million ha of forest (NRCan, 2018). At the landscape scale, higher amounts of edge habitat (caused by forest fragmentation) have been linked to an increased duration of forest tent caterpillar outbreaks (Roland, 1993), with outbreaks themselves occurring in cycles approximately every four to nine years, roughly corresponding to the El Niño Southern Oscillation and the resulting warmer spring temperatures (Chen *et al.*, 2018).

Forest pests can cause economic, environmental, and socio-cultural harm

While infestations can result in massive losses of forest cover, they also can cause significant economic harms for forest-dependent communities. Mainly due to tree mortality from the mountain pine beetle epidemic, the allowable timber harvest in British Columbia is projected to decline continually until 2025, when it is expected to stabilize (NRCan, 2020k). In areas that rely on the forestry sector, there are long-term economic impacts. Modelling estimates that, between 2009 and 2054, the cumulative loss due to the beetle will be 1.3% of British Columbia's GDP ($57 billion) (Corbett *et al.*, 2016). The decline in marketable timber is also expected to lead to job losses in British Columbia as a direct result of the mountain pine beetle epidemic (Corbett *et al.*, 2016). The potential spread of the beetle to the boreal forest would have devastating impacts, including lower merchantability of forest stands, as well as decreased carbon storage, losses in non-timber ecosystem services, and increased risks of wildfires (CCFM, 2019a).

The direct economic impact of non-native forest pests in the continental United States was estimated in 2011 to be more than US$4.9 billion per year, as a result of municipal, homeowner, and federal expenditures, as well as lost residential property and timber values (Aukema *et al.*, 2011). The introduction of the emerald ash borer has resulted in the mortality of ash trees across Canada (OMNRF, 2020). The spread of emerald ash borer, first discovered in North America in 2002 (Cappaert *et al.*, 2005), was facilitated by the movement of infested nursery trees, logs, and firewood (Siegert *et al.*, 2014). By 2013, emerald ash borer had been found in 21 U.S. states and 2 Canadian provinces (Ontario and Quebec) (Herms & McCullough, 2014). Mortality rates from emerald ash borer are high — some forests have lost nearly 100% of their ash trees in areas with the longest infestation history (Herms & McCullough, 2014). The deaths of otherwise healthy, mature trees cause substantial economic, cultural, and environmental losses. Emerald ash borer has been characterized as "the most destructive and costliest forest insect to invade North America to date" (Lovett *et al.*, 2016). Infestations cause an estimated US$280.5 million impact on municipal budgets in the United States, largely in tree and stump removal (Hauer & Peterson, 2017). The projected 30-year economic impact of emerald ash borer in Canada (from 2009 to 2039) was estimated to be between $0.5 to $1.5 billion (McKenney *et al.*, 2012).

Cultural losses from emerald ash borer are also expected, as, for example, black ash trees (*Fraxinus nigra*) are valued by the Anishinaabe and Haudenosaunee Peoples of the Great Lakes region for basket-making and other activities (Reo, 2005). Amid ongoing spread and infestation, Herms and McCullough (2014) speculate that the emerald ash borer may ultimately functionally extirpate one of the most widely distributed tree genera in North America, though some species, such as blue ash (*F. quadrangulata*) and white ash (*F. americana*), show host resistance (Tanis & McCullough, 2015), and some white ash stands have survived and show regeneration following infestation (Robinett & McCullough, 2019).

Threats from invasive forest pests change over time, requiring ongoing surveillance

In a global review of forest pests in 2009, the FAO identified six introduced insects of concern in Canada. These included the Asian long-horned beetle (*Anoplophora glabripennis*), the pine shoot beetle (*Tomicus piniperda*), the banded elm bark beetle (*Scolytus schevyrewi*), the LD moth, the European woodwasp (*Sirex noctilio*), and five species of adelgid (aphid-like insects), including the hemlock woolly adelgid (*Adelges tsugae*) (FAO, 2009). Of these, only the banded elm bark beetle is not a species of concern listed on the Forest Invasives Canada website as of May 2021; added to the list are the emerald ash borer, mountain pine beetle, southern pine beetle (*Dendroctonus frontalis*), spotted lanternfly (*Lycorma delicatula*), the brown marmorated stink bug (*Halyomorpha halys*), the elm zigzag sawfly (*Aproceros leucopoda*), and the brown spruce long-horned beetle (*Tetropium fuscum*) (ISC, 2021b).

Not all listed species of concern are known to occur in Canada; for example, after intense efforts to control the introduction of Asian long-horned beetle in Toronto in 2003, the CFIA declared it eradicated in 2013 (OMNRF, 2020). While a subsequent invasion was detected in August 2013 — clustered around the Toronto Pearson International Airport in Mississauga, Ontario — control efforts resulted in zero detections of the beetle in 2019 (OMNRF, 2020). However, evidence of forest pests may be difficult to detect at a landscape scale. In 2018, for example, foliar diseases (leaf damage and losses) were detected during ground surveys, but not through aerial surveys (OMNRF, 2019). Despite not being detected through aerial surveys, brown spot needle blight (*Mycosphaerella dearnessii*), spruce needle rust (*Chrysomyxa sp.*), and Armillaria root disease collectively resulted in reports of foliar damage in 2,042 ha of forest in Ontario in 2018 (OMNRF, 2019).

4.2.2 Agricultural Pests

Pest management is considered a substantial challenge for agriculture. For example, while wheat yields have been continually increasing from 1960 to 2017 in Canada due to technological advancements in crop breeding and agronomic practices, the gap between the potential yield (i.e., under ideal conditions) and actual yield has remained steady at about 24% over the same timeframe (Hatfield & Beres, 2019). While much of this gap between potential and actual yield is explained by the weather (i.e., precipitation), even with irrigated cropping systems, the yield gap only improves to about 80%, leaving about 20% of potential crop yield lost to other factors, including pests (Lobell *et al.*, 2009). A 2017 survey of experts in the U.S. Midwest and Canada estimated a soybean yield loss of 25% due to pests, with 9.3% of that loss a result of one pest alone — the cyst nematode (*Heterodera glycines)* (Savary *et al.*, 2019). Corn yield loss due to plant disease in

Ontario between 2012 and 2015 was over 113 million bushels or US$569 million — approximately an 8% loss in production (Mueller *et al.*, 2016). Prior to the commercialization of midge-resistant wheat cultivars (Box 4.5), wheat midge (*Sitodiplosis mosellana*) caused an estimated annual $60 million in crop-yield and end-use-suitability losses (Zheng *et al.*, 2020). Soltani *et al.* (2017) found that, without control measures, weeds had the potential to cause a 38% loss in soybean production in Ontario equalling nearly US$425 million. Climate change can alter the competitiveness of weed species, and pest management practices themselves impose selection pressures on pest populations, shifting the relative effectiveness of tools and strategies over time. While overall trends in agricultural pest populations in Canada are difficult to establish, it is notable that, over the past three decades, the proportion of cropland treated with pesticides (i.e., insecticides, fungicides, and herbicides) has increased across all regions (Malaj *et al.*, 2020).

Increasing temperatures and CO_2 are changing the distribution and biology of weeds

Changing climates allow weeds to establish in new areas and can make the conditions within current ranges more favourable (reviewed in Peters *et al.*, 2014). In North America, ranges for many weed species are expanding northward to regions that were once considered too cold for successful reproduction, including Canada (Clements *et al.*, 2014). For example, Japanese knotweed, an aggressive invasive species native to Asia, has shown rapid expansion in southern Ontario (Bourchier & Van Hezewijk, 2010), with warmer temperatures leading to an 18% increase in habitat in the early 2000s (Bourchier & Van Hezewijk, 2010). As of 2012, there are established populations of Japanese knotweed across southern, central, and eastern Ontario, as well as in the Atlantic Provinces and Quebec (Anderson, 2012a). Populations also exist in Winnipeg, Manitoba and across southern British Columbia. While the distribution of Japanese knotweed appears limited to warmer areas, it will likely expand northward with climate change (Anderson, 2012a). Increased levels of CO_2 provide many weed species with an advantage by enhancing their growth, reproductive output, and abundance (Korres *et al.*, 2016), making them more competitive relative to crops (Peters *et al.*, 2014). Studies have also shown that some weeds can grow at higher temperatures and in drought conditions more successfully than crops (Valerio *et al.*, 2011; Korres *et al.*, 2016). Overall, climate-induced changes in weed-crop competitiveness could make some weeds more difficult to manage (Grain Farmers of Ontario, 2019), increase the cost of weed control (Korres *et al.*, 2016), and lead to crop-yield losses (Clements *et al.*, 2014).

Pest management requires ongoing research and development

As Owen *et al.* (2014) state, "organisms adapt to all control tactics used in agriculture," meaning the exclusive use of a general pesticide will ultimately result in resistant pest populations. Alternatives or complements to synthetic pesticide use include biological control (i.e., the release of predators or parasitoids of the pest species) and bio-pesticides (i.e., the spraying of biological material — bacteria or viruses — that target pests) (Dixon *et al.*, 2014). The release of sex hormones or genetically engineered sterile insects to disrupt mating and reduce reproductive rates are recent innovations, and suppression techniques for insect pests are continually under development (Dixon *et al.*, 2014). Different strategies can be effective at reducing overall pesticide use, such as the planting of trap crops to attract target species to a controlled row or perimeter, which facilitates a targeted application of pesticides (Dixon *et al.*, 2014). Canada is one of the top 10 countries producing research and development of RNAi (ribonucleic acid interference) technology applications for agriculture (Mezzetti *et al.*, 2020). RNAi can specifically target and neutralize messenger RNA (mRNA), and applications include targeting plant genes to remove unwanted metabolites as well as targeting pests to suppress essential genes (Mezzetti *et al.*, 2020).

Effective pest management strategies require accurate identification of pest species, as well as quantification of the extent of their infestation. New technologies to complement visual identification of pests include field kits and lab testing. For example, the Barcode of Life Data System (BOLD) has archived DNA sequences for more than 77% of known plant arthropod pests; this can help to both identify threats and distinguish native and invasive pests that have similar appearances but differ in the severity of damage they cause (Ashfaq & Hebert, 2016). Field surveys can be supplemented with aerial drone surveys (to assess crop damage) and volumetric spore traps (to detect fungal pathogens) (Burchett & Burchett, 2018). Data from monitoring and surveillance, along with weather patterns, can be used to create predictive models for risk and to identify specific concerns for farmers in each growing season (e.g., Brook, 2016). Once information is collected and distributed, decision supports can help inform farmers about which actions will be the most cost-effective or efficient in maintaining plant health. These can include the publication of economic thresholds for pesticide application, recommendations for early-warning systems, and model predictions of pest emergence times (Dixon *et al.*, 2014).

Integrated pest management addresses the dynamic nature of threats from plant pests

Integrated pest management (IPM) reflects the integration of knowledge of pest species (e.g., biology, distribution, life history) with forecasting (e.g., weather forecasts, population models), control tools (e.g., pesticide applications, physical barriers), and cultivation practices (e.g., timing of planting, crop rotations, planting resistant varieties) to optimize the cost-effectiveness of control methods (Dixon *et al.*, 2014). The goal of IPM is to reduce reliance on pesticides, and is driven in part by cost considerations, the development of pesticide resistance in pest populations, and environmental and human health concerns around pesticide use (Dixon *et al.*, 2014). These have translated into changing government regulations and policy, and have shifted market demand from buyers, processors, and consumers (Gov. of QC, 2011; Dixon *et al.*, 2014). IPM is based on the biology and ecology of the pest and crop, the available control tools and cultural practices and their application, and decision support tools such as monitoring guidelines, early-warning systems, and economic thresholds for pesticide application (Dixon *et al.*, 2014).

IPM can be challenging as tools are lost — some older pesticides are removed from use due to regulatory re-evaluation; new pest threats emerge for which existing tools prove ineffective; or established pest populations adapt to climate change, pesticide use, or other changes to their habitat or ecology (e.g., changes in predator populations or interactions with invasive species) (Dixon *et al.*, 2014). Advances in IPM include stacking resistance to multiple pesticides within a crop; improved formulations of chemicals; research and development of new modes of pesticide action; and management strategies that include non-chemical controls, such as cultural, biological, and mechanical methods (Nandula, 2019).

IPM is supported by increased accessibility to information and infrastructure in order to develop better weather forecasts, degree-day forecasts, geographic and soil information, as well as refinement to economic thresholds for pesticide applications (Dixon *et al.*, 2014). For example, soil diagnostics are important for soybean cyst nematode IPM strategies, which help determine population densities of the pest prior to visible crop damage; such soil sampling is, however, time- and labour-intensive, and requires trained personnel (Legner *et al.*, 2021). One area of active research is in the development of a robotic instrument to automate sampling, with potential applications for other soil-pest diagnostics (Legner *et al.*, 2021).

While IPM strategies have been around for decades, the quality and optimization of an IPM program will vary by crop and region. For example, the IPM for wheat midge has been developed into a robust and well-used program over the course of 15 to 20 years (Box 4.5), whereas IPM programs for Canadian vineyards are relatively early in their development, with ongoing research on the identification and biology of pests and beneficial organisms (e.g., Lasnier *et al.*, 2019).

Box 4.5 IPM for Wheat Midge

The IPM plan for wheat midge is built on detailed knowledge of the biology, behaviour, and timing of crop susceptibility to this pest, accrued over multiple decades of research. In addition to having resistant cultivars (Gavloski & Meers, 2011), cultural practices for planting those cultivars reduce selection for resistance among the midges themselves (i.e., planting 90% resistant cultivars with 10% non-resistant wheat) (Dixon *et al.*, 2014). Indeed, growers who purchase Midge Tolerant Wheat varieties in Canada are required to sign a stewardship agreement with their retailer, committing to limit their use of farm-saved seed to one generation, in order to help preserve the effectiveness of the tolerance gene (Midge Tolerant Wheat Stewardship Team, n.d.). Other tools in the IPM plan include cultural practices for reducing midge in the soil, such as rotating with canola, flax (*Linum usitatissimum*), and legumes, as well as other field crops such as barley (*Hordeum vulgare*) and oats (*Avena sativa*) (Dixon *et al.*, 2014), and for supporting populations of the native wasp *Macroglenes penetrans*, a parasitoid of the wheat midge (Elliott *et al.*, 2011).

Decision support tools in the IPM plan include established economic thresholds for insecticide application, forecasts, and early-warning systems (Dixon *et al.*, 2014). Before planting, forecast maps provide information to farmers so they can decide whether to plant a non-resistant variety of wheat, a resistant variety, or an alternative crop. They can also decide to plant early (to avoid the convergence of midge population emergence with the most susceptible wheat developmental stage) or to plant a less susceptible cultivar. After planting, there are monitoring and field scouting tools (e.g., visual counts, sticky cards, pheromone traps) to inform ongoing decision-making during the growing season. There are known parameters for maximizing the effectiveness of insecticide applications while minimizing potential impacts on crop value and beneficial insects (e.g., applying only when detection levels reach one adult per four to five wheat heads, and when the crop is heading but not yet flowering). Late applications of insecticides are neither cost-effective nor good for maintaining the populations of beneficial parasitoids (Dixon *et al.*, 2014).

Precision agriculture can provide data for integrated pest management

Precision agriculture aims to use "data intense approaches to drive agricultural productivity while minimizing its environmental impact" (Liakos *et al.*, 2018). Specifically, precision agriculture is a crop management system based on data-driven analysis of spatial and temporal variability in crop and soil factors (Stafford, 2000). Crops are managed through metrics including yield prediction, disease detection, weed detection, crop quality, and species recognition (Liakos *et al.*, 2018). For example, precision agriculture can be used to identify consistently unprofitable areas of cropland, which can then be planted with alternative species — for pollinator forage, animal fodder production, erosion control, or nitrogen fixation — to accrue environmental benefits and avoid crop losses (Capmourteres *et al.*, 2018). By providing accurate estimates of pest incidence and severity, as well as quantifying the negative effects of pests on the quantity and quality of field crops, precision agriculture could also provide a basis for targeted interventions to address plant health risks (Mahlein, 2016).

Ideally, data collected in precision agriculture allow for the detection of diseases, insects, or weeds at early time points, differentiation among different diseases, identification of which diseases are caused by abiotic stresses, and the assessment of disease severity (Mahlein, 2016). Sensors can be installed on different devices (e.g., tractors, robots, aircrafts, satellites) or be stationary at strategic points (Mahlein, 2016). In the literature on precision agriculture, there are several examples of actions aimed at disease detection in wheat, such as the detection of nitrogen-stressed versus yellow rust-infected wheat in comparison to healthy wheat crops (e.g., Moshou *et al.*, 2004, 2014; Pantazi *et al.*, 2017). Monitoring challenges include the ability to recognize disease symptoms and damaging insects and weeds, as well as the time and effort needed to assess not only the presence or absence of plant health risks (incidence), but changes in abundance as well (severity) (Weersink *et al.*, 2018). Ground-truthing (i.e., "boots in the field") is important for ensuring the accuracy of inferred plant health states from data collected through sensors. Other challenges in the adoption and effective use of precision agriculture include the need for new equipment, expertise, and infrastructure, among other elements (explored further in Section 5.2.1).

Effective weed management is critical for the success of agriculture in Canada

An effective weed management system incorporates a diversity of crop types, weed-competitive crops and practices, and pre- and post-herbicide application surveys to identify target weeds and determine effectiveness of applications (as well as monitor for resistance) (Beckie & Harker, 2017). Mechanical control of weeds is largely accomplished through tillage and hand weeding (Khan *et al.*, 2019b). However, harvest weed seed control systems, which mechanically target and destroy weed seeds during harvest, have been increasingly developed and deployed in the face of herbicide-resistant weed populations, including on the Canadian Prairies (Walsh *et al.*, 2018; Hein, 2021). Biological control can be attempted through the introduction of insects to manage some weed species; this has had limited successes, though outcomes vary in geographic location and over time (Appleby, 2005). Research and commercial application of fungal and bacterial weed pathogens as myco- and bio-herbicides, respectively, has also met with limited success (Appleby, 2005).

Research on enhancing crop competitiveness and improving weed management strategies is critical for the long-term success of agriculture in Canada. Some current research areas include the targeted application of non-selective herbicides on early germinated weeds ("stale seedbed"); changing the row spacing, planting density, row orientation, and timing of sowing to improve crop competitiveness; developing more competitive cultivars; improving modelling of weed outbreaks; remote sensing to provide better data on weed emergence and problem areas; and the application of robotic and automated technologies to targeted weed removal or herbicide applications (Kumar *et al.*, 2020). However, weed management strategies themselves will shift selection pressures on existing weed populations, and may create habitat for different weed species. A better understanding of weed ecology and genetics, as well as their ecological functions, will also help to improve weed management and identify trade-offs in management practices (Clements *et al.*, 2004).

4.3 Risk Management

The introduction and establishment of novel plant pest populations are inevitable, as are changing climatic conditions and the adaptation of some existing pest populations to control measures. In addition to surveillance and biosecurity to reduce the risk of pest introduction and spread, mitigation measures to protect plant health must also consider reducing the vulnerability of plant systems to catastrophic failures of ecosystem function. Vulnerability may be addressed by management practices that support biodiversity and redundancy in ecosystem functions in forestry and agriculture.

4.3.1 Forest Management Practices

Future forest health will be impacted by how well biosecurity regulations and enforcement limit new invasions, which requires research and the development of better monitoring techniques and technologies, models to target priority areas and species, and mitigation strategies for established pests. Improving current forest management practices depends on the growth of practical theory and knowledge on the determinants of pest abundance, as well as how biotic and abiotic conditions affect tree and pest growth, reproduction, and interactions (Ayres & Lombardero, 2017). However, changing forest management practices to support biodiversity and redundancy in ecosystem functions is necessary to increase the overall resilience of forest systems (recall Box 3.5).

Aerial forest herbicide application may impact the health of non-target plants

In Canada, the aerial spraying of herbicide — mostly glyphosate — immediately following forest harvest activities is used to control the fast-growing early competitors of planted seedlings (Thompson *et al.*, 2012). Aerial applications of glyphosate in 2018 covered 26,839 ha of forests in Alberta, 784 ha in Manitoba, 33,960 ha in Ontario, 15,161 ha in New Brunswick, and 296 ha in Newfoundland and Labrador (NFD, 2020). An unspecified herbicide (thought to be mostly glyphosate, but details are not available) was applied using unspecified means to 12,420 ha of forest in British Columbia in 2018 (NFD, 2020). Following the development of its *Forest Protection Strategy*, the Government of Quebec banned the use of chemical herbicides in forests in 2001 over concerns about their harmful effects on the environment and human health (Thiffault & Roy, 2011). Public demand for similar bans on aerial spraying of herbicides is growing in other provinces (e.g., White, 2019; Thompson, 2020). There is conflict over aerial spraying of glyphosate in northern Ontario, where forests support both timber operations and blueberry harvesting (Stolz, 2018). In addition to direct damage to blueberry plant health by glyphosate (Stolz, 2018), concern also exists over the implications for human health in areas of overlap with edible and/or medicinal use of native plants (Wood, 2019).

Biodiversity, as well as diversity in management practices and perspectives, is important in addressing risks from forest pests

In a review of a global network of tree diversity experiments (TreeDivNet), Grossman *et al.* (2018) note that tree diversity often improves the survival, and can increase growth, of young trees. The application of techniques to measure functional diversity and complex spatial networks in forest management can help direct stewardship actions to strengthen a forest's natural adaptive ability, productivity, and resilience in the face of global change (Messier *et al.*, 2019). By providing more than one good or service from a given area of land — for example, not only timber but also wood-based bio-energy, climate change mitigation, water storage, recreational activities, ecosystem services, and non-timber forest products

— forests can be multifunctional, offering both economic and non-economic benefits (Mansuy, 2016).

Forest management is facing unprecedented pest challenges, including rapid range expansions of native forest pests following warming climates and an increasing number of novel pest introductions via intercontinental trade and travel (Ayres & Lombardero, 2017). As mentioned in Section 3.5.1, forest management practices have traditionally focused on optimizing timber production to maximize economic returns (Menzel *et al.*, 2012; Rico & Gonzalez, 2015). This practice is gradually being replaced by multifunctional decision-support systems that use a broader definition of value, one that includes social, ecological, and economic components (Sheppard, 2005; Menzel *et al.*, 2012; Rico & Gonzalez, 2015). Moreover, achieving broader objectives will require ongoing efforts in prioritization, negotiation, learning, and adaptation among multiple actors (Mansuy *et al.*, 2020). For example, molecular techniques for detecting forest pests can substantially improve detection probabilities (i.e., the current or recent presence of a pest), but do not provide information on abundance or disease status (Lamarche *et al.*, 2015). Uptake of these molecular techniques outside of select academic and government programs is therefore challenged by uncertainty over commercial viability and how information from this technology may be translated into regulation and policy, particularly for international trade (Hall *et al.*, 2019). Regional, national, and international communication and information sharing are key to addressing challenges associated with domestic and international movements of intentionally imported and hitchhiking pests (Ayres & Lombardero, 2017).

4.3.2 Agricultural Management Practices

Agricultural producers actively plant the land, manage nutrient and water inputs, and attempt to minimize damage from pests to maximize profitability — usually measured by growth or reproductive output (i.e., seeds and fruits). The fine-tuning of crop and habitat involves balancing short-term returns and long-term sustainability, and can reveal unexpected relationships among different crop characteristics, such as resistance to pests or drought, competitiveness, or nutritional quality.

Breeding technologies have been widely adopted as pest management tools for certain crops in Canada

Advances in breeding technologies led to the development of commercial varieties of herbicide-tolerant crops, particularly tolerance to glyphosate and glufosinate, as well as the development of crops that produce *Bacillus thurigiensis* (Bt) toxins as a built-in insecticide (Bt is a pathogenic bacteria of insects) (Meyer, 2011).

The commercialization of glyphosate-tolerant crops in the mid-1990s (Monsanto's Roundup Ready crops) provided a simple and effective solution to weed management, allowing growers to apply a highly effective, broad-spectrum herbicide to control weeds without damaging crops (Duke & Powles, 2009). Herbicide-tolerant canola was first introduced commercially in 1995; by 2005, 95% of canola varieties planted were estimated to be herbicide-tolerant to glyphosate, glufosinate, or imidazolinone (Beckie *et al.*, 2006). Following their introduction in 1997, herbicide-tolerant soybean crops constituted about 60% of those grown in Canada in 2005 (Beckie *et al.*, 2006). In 2018, 95% of soybean planted was herbicide-tolerant (ISAAA, 2018). Less than half of all corn planted in Canada in 2005 was herbicide-tolerant (Beckie *et al.*, 2006). Since then, corn varieties that include herbicide-tolerant, as well as stacked insect-resistant and herbicide-tolerant varieties, have reached close to 100% adoption (ISAAA, 2018).

However, economic realities, available genetic diversity, and consumer preferences impose constraints on breeding. In addition to disease resistance, crop varieties will be more economically viable if they are uniform in growth and development, high-yielding, efficient (e.g., in water and nutrient use), and high-quality (e.g., taste, nutrient content) (Burchett & Burchett, 2018). A suite of innovations, such as different breeding technologies, cultivation practices, and chemical interventions, is necessary to ensuring options are available to effectively manage risks to plant health in agriculture. Moreover, the Panel notes that the availability of different tools and practices is not sufficient — choices must also be made regarding the appropriate and timely use of different tools and practices, which, in turn, will depend on factors such as local soils, weather forecasts, skills and education, availability of equipment, and costs, among others.

Crop rotations reduce vulnerability of crops to pest outbreaks

Crop rotations in agricultural systems can foster diversity in plant species, which can increase yield stability, reduce the incidence and impacts of pests, and protect soil health (Thiessen Martens *et al.*, 2013). For example, rotations of corn and soybean with legume cover crops improved yield stability and decreased the risk of crop failure over a 31-year study in Ontario (Gaudin *et al.*, 2015). Clubroot, a disease caused by the parasite *Plasmodiophora brassicae*, results in swollen growths on the roots of Brassicaceae plants (which include turnip, cabbage, and canola) that reduce water and nutrient uptake, and can lead to complete crop failures under severe infections (Strelkov & Hwang, 2014). Clubroot survives in soils over multiple years and is established in many vegetable-growing regions of Canada, including the Maritimes, Quebec, Ontario, and British Columbia. Clubroot has only recently been found to affect canola plants, first in Quebec in 1997 and then in Alberta in 2003 (Strelkov & Hwang, 2014).

Because canola production is a multibillion-dollar industry, the economic risk of a severe clubroot outbreak is high. While clubroot management strategies have included the registration of resistant varieties, research has also emphasized the importance of crop rotation in reducing vulnerability to severe infestation (Strelkov & Hwang, 2014). For example, even with resistant cultivars, a rotation of one canola crop every four years is recommended, in part to maintain the durability of resistance (Strelkov & Hwang, 2014; Gov. of AB, 2021b). However, investigation of a recent introduction of clubroot to fields in Peace Country, Alberta revealed that all clubroot-infested fields used short crop rotations with canola in high frequency, planting these crops three to six times over a seven- to eight-year period (Strelkov *et al.*, 2020). Across Alberta, the most severe outcomes (i.e., yield losses of 30 to 100%) have occurred in fields where canola is cropped every year or every second year (Strelkov & Hwang, 2014).

Diversity in agricultural practices can reduce vulnerability to plant health risks

In a study of agriculture in the United Kingdom, Abson *et al.* (2013) found that increases in diversity of land use (e.g., cropping systems, animal production) reduce the variation in expected returns, providing greater economic stability. However, there is a trade-off between diversity and expected returns — higher diversity decreased the economic return from any one land use and, for operations of greater than 1,200 ha, there was no effect of diversification on economic resilience, likely due to economies of scale (Abson *et al.*, 2013). While the average farm size in Canada is below this threshold (recall Figure 1.1), some grain and oilseed farms on the Prairies can exceed 5,000 ha in size (Brown, 2017). Some agricultural practices to support diversity are well established, effective, and relatively simple to implement, such as changing crop species and varieties year-to-year, and new cultivars of commercial crops are being developed and registered every year (Thiessen Martens *et al.*, 2013). Other farming practices require research and development to determine their applicability and effectiveness across different agricultural settings, such as the development of high-yield perennial crops (Table 4.1). Still other farming practices may be relatively well established in some contexts, but require ongoing research to adapt to local conditions, such as the use of winter cover crops on potato (*Solanum tuberosum*) fields to reduce soil erosion and associated losses of carbon and nitrogen during snow melt (AAFC, 2020d). For organic farming in Canada, the national standard for organic productions (CAN/CGSB-32.310-2020) requires producers to include measures that promote biodiversity, such as the incorporation of pollinator or wildlife habitats, or the maintenance or restoration of wetlands (CGSB, 2020).

Table 4.1 Examples of Practices That Support Diversity in Canadian Agriculture

Practice	Adoption	Ongoing Research
Changing crop variety	Widely used	• Suitability of modern and heritage varieties to different cropping systems • Targeted breeding programs, including for organic varieties
Crop selection and rotation	Widely used	• Targeted breeding for local adaptation • Decision supports for developing rotations
Fall-seeded crops, cover crops, and intercropping	Variable use in different locations	• Interseeding/relay cropping • Double cropping • Self-regenerating cover crops • Cover crops for weed suppression • Grain intercropping • Balancing cash and cover crops to optimize benefits
Perennial crops (e.g., in rotation, green manures, polycultures)	Common in Canadian prairie forage crops, Indigenous forest gardens	• High-yield perennial grains (e.g., wheatgrass) • Developing viable options for Canadian winters
Agroforestry	Shelterbelts and windbreaks widely used	• Ecobuffers • Tree-based intercropping/alley cropping
Agroecosystems	Grazing is common in perennial forage-based systems	• Farmscaping (e.g., riparian area management — maintenance, establishment, re-establishment) • Integrated plant and livestock and grazing

Source: Thiessen Martens *et al.* (2013); Armstrong *et al.* (2021)

Implementation of diverse farming practices relies on financial and community supports to manage the economic risks of adopting new methods and accelerate learning. Financial supports can include crop insurance, payment for ecological goods and services, as well as government risk management programs and subsidies (Thiessen Martens *et al.*, 2013). Many of these farming practices may only be profitable if the product is sold at a premium, which might be achievable with local, integrated supply chains, but may not be economically feasible for commodities produced for export to the global market. Other practices, such as payment systems for ecological goods and services, have been proposed, but not yet implemented. Community supports include national, regional, and local growers' groups that provide educational programming and resources, as well as opportunities to socialize and share experiences (e.g., Beach *et al.*, 2018; COG, n.d.). The Government of Canada protects the intellectual property rights of plant breeders, whereby registering a new variety gives the holder exclusive rights to "control the sale, production, reproduction, import, export, conditioning and stocking of their variety," ensuring compensation and encouraging investment in plant breeding (ISED, 2021). Research programs can offer financial supports as well as opportunities to build community among producers (e.g., POGA, 2021). For example, the Participatory Plant Breeding projects, supported by the Bauta Family Initiative on Canadian Seed Security and AAFC, bring together university researchers, funding agencies, and farmers in plant breeding programs that select for varieties of field crops (wheat, oat, potatoes, and corn) as well as vegetables adapted to their regional climate and farm needs (Entz *et al.*, 2020; CANOVI, n.d.).

5

Governance Risks to Plant Health

Chapter Findings

- Communication and coordination among government departments and agencies with similar mandates, but different priorities, may result in gaps in surveillance and the introduction of plant health risks.
- Networks that connect the research and work of academics, governments, Indigenous Peoples, NGOs, industry, citizen scientists, and other relevant actors are essential in successfully deploying resources and knowledge to mitigate and manage emerging risks.
- Insufficient expertise, unclear regulations, and lack of coordination governing the effective management of data present challenges in adopting and applying promising practices, such as new surveillance technologies.
- Trust is earned by engaging the public early in the decision-making process and through consideration of cultural and social values. Public engagement can be a valuable tool to identify plant health risks and to create effective policies.

A full analysis of the risk environment cannot be made without consideration of governance risks, which are those associated with the function of the plant health system itself — most notably the system's social and policy dimensions (Mills *et al.*, 2011; Pautasso *et al.*, 2015). A risk governance framework considers a variety of actors, conventions, processes, and mechanisms in determining how information is collected, assessed, managed, and communicated, as well as how decisions are made (Aven & Renn, 2010; IRGC, 2019).

The Panel identified several broad areas of risk in the governance of Canada's plant health system. These include:

- a lack of coordination and communication among actors, and a lack of clarity within the plant health system;
- the volume, velocity, and availability of new technologies and data designed to improve the surveillance of the state of plant health, and risks to plant health; and,
- issues of public trust in science and governance.

Each of these broad areas has the potential to create or exacerbate known and unknown risks. Furthermore, these identified risk areas are often intertwined.

For example, a lack of public trust may lead to more stringent regulations that impact the timelines of available tools used in the field to manage plant health risks.

5.1 Communication and Coordination: The Challenges of a Federated System

Given the number and variety of actors in the plant health system (see Section 1.5), cross-communication and collaboration are vital to the exchange of information, the expression of interests, and the formation, enacting, and monitoring of policy. Speaking to the British experience, Pautasso *et al.* (2012) note that "a promising development is the increased interdisciplinarity in research on plant health, as well as the improving involvement of stakeholders in plant disease management." However, even with improvements, problems persist, and these problems pose risks to plant health (Pautasso *et al.*, 2012). The Panel believes that this sentiment can be equally applied to the Canadian context.

5.1.1 Lack of Coordination and Plant Health Risk

International governments, federal agencies and departments in Canada, their provincial and territorial counterparts, and municipalities all play a role in the governance of the plant health system (recall Table 1.2). In many ways, these actors strengthen the Canadian system and help to create a comprehensive approach and lessen system-wide gaps. The Panel notes that, to date, catastrophic failures in the plant health system have largely been avoided, which may indicate that the system is generally working.

The plant health system is, however, increasingly encountering new and greater environmental and ecological stressors, which pose larger challenges. The multitude of actors can also present the system with challenges, including legislated mandates that have competing (or conflicting) goals and priorities, which can lead to potential oversights, duplicate or overlapping services, and failures to coordinate and share information and research (CFIA, 2019a; Giovani *et al.*, 2020). While the Panel has, to the best of its ability, identified the relevant actors in the governance of the plant health system, there is little information describing how the CFIA and other actors interact and coordinate. This may suggest a lack of standard operating procedures that prevents a fully coordinated plant health strategy with clear roles and responsibilities. In the absence of effective mechanisms to communicate and coordinate planning, management, and surveillance across agencies, Canada runs the risk of failing to identify and respond to present and emerging risks to plant health.

There are a diversity of interests in the plant health system

Competing paradigms such as those outlined in Chapter 1, and a diversity of interests among actors in the global and Canadian plant health systems, mean that there are instances where goals and priorities fail to align, resulting in different strategies for managing risks to plant health. Furthermore, differing values may result in a variety of perspectives on what may constitute risk, on risk tolerance, and on best practices to address them. Each strategy may have different trade-offs. For example, a paradigm that prioritizes short-term productivity may trade off prioritizing actions to promote sustainability and resilience. The challenge lies in finding solutions that balance the multiple functions (i.e., economic, social, cultural, environmental) of agricultural and forest ecosystems.

While Canadian policies have shown a shift toward what has been described as a multifunctionality paradigm, typically economic values remain dominant in driving management of agriculture and forestry systems (Skogstad, 2012; Messier *et al.*, 2015). In the absence of (i) a governance structure with clearly specified roles, responsibilities, and operating procedures, and (ii) clearly articulated values (in which policies are rooted), conflicts among goals and priorities may allow potential risks to plant health to escape detection or go unmonitored.

Competing priorities between international obligations and domestic interests may result in conflicts and risks

As part of a global trading system, Canada (like all countries) must balance international obligations and domestic economic interests, public safety, and ecological protection. Within existing international frameworks related to plant health, a lack of communication and unclear or difficult-to-implement guidelines can create or exacerbate risks to plant health (MacLeod *et al.*, 2010). For example, a lack of resources in some nations may prevent the communication of potential risks, or the implementation of adequate quarantine or risk assessment systems, thereby allowing plant pests or diseases to spread (MacLeod *et al.*, 2010; Ristaino *et al.*, 2021). Furthermore, while the purpose of a treaty such as the *International Plant Protection Convention* (IPPC) (recall Table 1.3) is to harmonize goals and rules governing plant health among nations, agreement about, and coordination of, goals and priorities remains difficult (Shine, 2007). Nations may have differing perspectives on the appropriate balance between trade rules and environmental protection, or between international commitments and domestic concerns (MacLeod *et al.*, 2010; Maye *et al.*, 2012). While existing treaties and agreements are based on international consensus, they also ensure that national governments retain the right to implement measures in the interest of protecting their own citizens and environment from the importation of pests (MacLeod *et al.*, 2010). However, even with that right, the *Agreement on the Application of Sanitary and*

Phytosanitary Measures (SPS Agreement) mandates that these protective decisions be scientifically based and the least trade-restrictive (WTO, 1995).

It has not been uncommon for conflicts between protection and trade goals, and the "vagueness of the wording" of the SPS Agreement, to create situations pitting national interests against international cooperation (Anderson *et al.*, 2001). To date, there is no mechanism that can perfectly weigh plant health risks against international obligations. Furthermore, despite international rules and agreements, plant health issues and trade repercussions may be used as a proxy for unrelated geopolitical issues, making both producers and consumers subject to political conditions that impact the import and export environment. This has purportedly been the case, for example, in the trade of canola to China from Canada (Wang & Leblond, 2019; Canola Council of Canada, 2020).

To protect plant health, as well as international trade, it has been suggested by Canada's Economic Strategy Tables and others that Canada play a more active role in international standards-setting bodies (ISED, 2018; CFIA, 2019a). An investment of resources in these bodies to further develop science-based standards, as well as funding to increase the participation of Canadian agencies and promote their leadership, could improve Canada's trade relationships and provide further opportunities to promote adherence to science-based regulatory frameworks (ISED, 2018; CFIA, 2019a).

Competing goals and priorities within the governance structure may result in conflicts and failures in oversight

Within the governance of plant health in Canada, some departments and agencies have similar mandates but different priorities; this may result in oversights that allow for deficiencies in surveillance and the introduction of plant health risks. It has, for example, been an ongoing issue in the surveillance and management of biosecurity risks at international borders, a responsibility that is shared between the CFIA and the Canada Border Services Agency (CBSA) (Box 5.1). While both federal agencies play an essential role in the protection of plant health, limited resources (e.g., staff, budget) and different departmental priorities (i.e., biosecurity vs. a broader security mandate) have created a security gap in monitoring and surveillance, thereby increasing the risk of the introduction of invasive pests into Canada (OAG, 2008; CFIA, 2015).

Box 5.1 Shared Responsibilities Between the CFIA and the CBSA

Since signing a memorandum of understanding (MOU) in 2005, the CFIA has worked with the CBSA to regulate product entry at borders and ports (OAG, 2008). The CFIA has no staff presence at the border, but instead relies on the CBSA "to identify and prevent potential threats to the Canadian plant resource base from crossing the border into the country" (CFIA, 2015). In exchange, the CFIA provides the CBSA with input on training and the technical assistance required to fulfil CFIA objectives (CFIA, 2015). While the intent of this partnership is the exchange of information, a 2008 review by the Office of the Auditor General of Canada (OAG) found a lack of coordination and communication between the two agencies. As a result, the CFIA's own ability to track pests and comply with its mandate was limited. Furthermore, the CBSA routinely prioritized the certification of exports over imports to avoid delays at the border, increasing the risk of pest introduction through imports (OAG, 2008).

While the 2008 OAG report resulted in a commitment between the CFIA and the CBSA to improve inter-agency communication, a 2015 internal review of the CFIA's Plant Protection Program (PPP) found continuing problems, including concerns expressed by CFIA informants that the CBSA, in its surveillance of borders, routinely "prioritizes plant protection below the regulation of drugs, firearms, and other such commodities" (CFIA, 2015). It was recommended that a review of the relationship between the CFIA and the CBSA be made to "optimize programming options" (CFIA, 2015). Since 2015, no further updates on the relationship between the two agencies have been published.

The differing values and priorities of the many actors in the plant health system can prove challenging in both defining risk and determining the appropriate methods or levels of risk management. For example, while both agricultural producers and environmental interest groups value environmental sustainability and biodiversity, their priorities and risk tolerance may vary. In the case of the use and management of pesticides, producers and trade associations may prioritize access to the tools necessary to manage their lands and compete in terms of production, thus making them more tolerant of pesticide use and its potential impacts. Environmental NGOs, Indigenous actors, and others, conversely, may prioritize the stringent regulation of pesticides, viewing pesticides themselves as the dominant risk to plant health. Of course, within this continuum many nuances exist. Given the plurality of perspectives among the actors in the plant health system, it is important for government departments and agencies such as AAFC, the CFS, and the CFIA to find ways to make explicit the values that are driving their policies, and the tensions and risks that may arise from their stated priorities — whether they be shaped by economic, environmental, safety, or security considerations. This transparency is especially vital in the present-day context, where public scrutiny of policies related to food production and the environment is high, and where existing paradigms have been challenged by critics interested in both new policy goals and in new forums for decision-making (Skogstad, 2012).

There are risks of duplication and a lack of clarity in the plant health governance system

There is significant overlap in the roles of various orders of government in Canada. Environmental protection, for example, falls under the jurisdiction of both federal and provincial or territorial governments. Because of this, a single issue can involve multiple decision-makers. Take, for example, the forestry industry and its related products. As noted in Section 1.5, for the most part provincial and territorial governments control forestry resources, yet the federal government maintains jurisdiction over issues related to international trade and commerce (GC, 2012). Adding further complexity, provinces and territories often lease public forests to private companies, giving these companies the right to manage forests for prolonged periods (Haley & Nelson, 2007).

Cross-cutting issues among the CFIA and other departments and agencies present opportunities for cooperation, but they can also lead to duplication of work, resulting in wasted time and resources (CFIA, 2019a). A targeted regulatory review of the agri-food and aquaculture sectors in Canada — conducted in 2019 and involving several relevant federal agencies (including the CFIA) — cited cases that speak to these issues, and identified the need for "clear, agile, responsive regulations" (CFIA, 2019a). The review found that, while the Canadian regulatory system is generally well respected, reliably science-based, and considerate of safety standards, there is room for simplification to support growth and innovation in a number of areas, including the regulation of new products impacting plant health such as pesticides (CFIA, 2019a).

Some agricultural producers, grower groups, and trade associations have noted that Canada's pre-market assessment and authorization timelines for innovations in feed, seeds, fertilizers, and plants with novel traits are slow, and do not adequately facilitate industry needs (CFIA, 2019a). While these inefficiencies have been cited as a factor in limiting Canadian competitiveness in the global agricultural marketplace (ISED, 2018; CFIA, 2019a), they can also impact plant health when innovations that may protect against new pests, for example, cannot be used by producers because they are held up in the regulatory process.

Some of the inefficiencies of the regulatory process related to pesticides have been attributed to the fact that both Health Canada and the CFIA share jurisdiction on this issue (CFIA, 2019a). As the lead agency on pesticide regulation, Health Canada's top priority is public health and safety. While the department has proposed regulatory changes, it remains imperative that any changes be considered against potential risks to human and environmental health. The challenge of creating an effective regulatory system for pesticides is one of balancing timely access to new tools and products in a way that allows producers to manage plant health risks, with the continued protection of public safety and other considerations, including environmental sustainability and the protection of biodiversity. This balance of competing interests may lead to decisions that fail to fully appease any party, such as in the case of the partial ban of neonicotinoids (Box 5.2). Even with these conflicts in mind, there is agreement among actors and regulators that aspects of the current system for evaluating pesticide products — including incident reporting, labelling requirements, authorization of non-registered pesticide products, and the re-evaluation process — are priority areas for improvement (CFIA, 2019a).

Box 5.2 The Regulation of Neonicotinoids

The use of neonicotinoids has been a contentious issue for agricultural producers, environmental groups, and beekeeper associations; these pesticides protect crops against insects, but can also be harmful to the health of pollinators, including honeybees (Singla *et al.*, 2020). In response to pollinator health concerns, Canada cancelled the use of three neonicotinoids (imidacloprid, thiamethoxam, and clothianidin) on fruit trees, flowers, and other plants that attract bees (HC, 2020). Regulators, however, did not put a full ban in place, allowing for the continued use of neonicotinoid-coated canola and cereal seeds (Ballingall, 2019). Some provinces also have additional restrictions in place; in Ontario, neonicotinoids are limited to corn and soybean seeds (Gov. of ON, 2020a), while farmers in Quebec require permission and prescriptions from agronomists to purchase and apply neonicotinoids and neonicotinoid-treated seeds (Gov. of QC, n.d.-b).

Issues of jurisdictional control may cause confusion and pose risks to plant health

Canada's system of governance, in which each jurisdiction (e.g., federal, provincial, territorial, municipal) has its own roles and powers, can result in a patchwork of policies without alignment. While this system is designed intentionally to separate and delegate jurisdictional powers, it can be challenging in the case of some plant-health-related issues that defy simple jurisdictional organization, such as the control of invasive species that do not abide by borders, whether they be international or interprovincial. Internationally, there is limited cooperation in monitoring borders.

However, the IR-4 Project, based in the United States, works with AAFC and its provincial representatives and U.S. counterparts to protect specialty crops through the management and mitigation of pests of shared concern (The IR-4 Project, n.d.-a, n.d.-b). Within Canada, invasive species are managed by several actors. While the CFS focuses its work on invasive species in forests, its power is limited as provinces and territories are primarily responsible for forest management. Additionally, some provinces, territories, and municipalities may have their own invasive species legislation or bylaws, and municipal powers may be regulated in part by the province or territory (ISC, 2021a). Ontario's *Invasive Species Act* (2015) regulates the prevention and management of 20 recognized invasive species in Ontario, while the *Municipal Act* (2001) manages and regulates jurisdictional powers in Ontario and its municipalities, which includes public parks, roadsides, and other spaces that may be impacted by any non-native species (ISC, 2021a). While this approach addresses a variety of regions, without concerted efforts at comprehensively managing and sharing relevant information, it risks the creation or persistence of knowledge gaps in the identification and management of invasive species.

Coordination can also be challenged by shifting political priorities. As governments potentially change with election cycles, agencies may struggle to maintain consistent approaches. Coordination is particularly relevant for issues such as climate change, which has a wide scope and whose remedies require intensive and early planning. For example, while Environment and Climate Change Canada (ECCC) is the federal lead on climate change, the issue is broad enough to impact multiple departments and agencies, and it necessitates high levels of leadership and coordination (OAG, 2017). An OAG (2017) report found that ECCC, up to that point, had failed "to provide adequate leadership and guidance to help departments and agencies adapt to a changing climate." This included a failure to share its resources and information related to promising practices to improve decision-making and planning across the government. It was also noted in this report that a centralized portal with resources (e.g., climate change data) and tools (e.g., training materials) would facilitate the exchange of information, expertise, and promising practices. In its assessment of other departments and agencies, the OAG found that, while NRCan had completed a comprehensive risk assessment related to climate change (i.e., incorporating identified risks and adaptation strategies into its programs and activities), other departments involved in the protection of Canada's plant health — including AAFC, the CFIA, and Parks Canada — had failed to do so. According to the OAG, this "matters because without a clear understanding of climate change risks, it is difficult to manage them properly" (OAG, 2017).

MOUs can also help to clarify roles and responsibilities and to foster collaboration among federal departments and agencies, as well as among orders of government. For example, there are MOUs between the CFIA and the Pest Management Regulatory Agency (PMRA) regarding the regulation of pest control products, and between the CFIA and the CBSA on issues of border security (recall Box 5.1).

Collaboration helps ensure preparedness for future risks

Collaboration among actors and across sectors may help to predict, manage, or react and adapt to future plant health risks, including those that may result from catastrophic events. For example, because of COVID-19, structural problems in the food system became apparent in 2020, including gaps related to failures of collaboration and coordination (Blay-Palmer *et al.*, 2021). According to Blay-Palmer *et al.* (2021), COVID-19 helped to lay bare the importance of multi-actor planning and preparedness in order to build resilience in the system, as well as the development of quantitative and qualitative tools to measure progress in preparedness.

Conducting regular exercises to stress-test the existing plant health governance system may be a way forward in preparing for, and protecting against, future catastrophes. These types of tests and risk responses are already conducted with regularity across the animal health system. For example, based on historical responses to animal disease events (e.g., bovine spongiform encephalopathy, avian influenza), the CFIA has developed emergency response structures that are regularly stress-tested (CFIA, 2021). Currently, African swine fever (ASF), an active disease in various parts of the world, is of major concern for its potential impacts on the Canadian hog industry. To prepare for the possible introduction of ASF in Canada, the CFIA is conducting preparedness training that includes seminars and courses for CFIA staff and private veterinarians in ASF detection, as well as identifying partners and establishing guidelines for all steps of a potential introduction — from the implementation of biosecurity measures to data management and public communication. The CFIA has established and runs through various action scenarios that test its response against several potential outcomes, including ASF detection on Canadian farms, in wild populations in Canada, on U.S. farms, and in other global locations. Each scenario anticipates potential challenges, impacts, and responses (CFIA, 2021). There is no evidence indicating that preparedness exercises or stress-testing are currently underway with counterparts in plant health, but this example from animal health may provide a relevant framework for consideration.

While the scale of stress-testing that occurs in animal health is not currently in place for plant health, the CFIA has in the past responded successfully to smaller-scale incidents through collaborative agreements and actions among different jurisdictions. This occurred in 2020, for example, when potato wart (*Synchytrium endobioticum*) was detected in Prince Edward Island (Box 5.3).

Box 5.3 Potato Wart in Prince Edward Island

In 2020, the presence of potato wart, a fungal disease that renders potatoes inedible and can have long-term impacts on soil health (Franc, 2007), was detected on a farm in Prince Edward Island (Spud Smart, 2020). Quickly, the CFIA, in collaboration with provincial authorities and industry partners, imposed quarantine measures, conducted surveillance, and controlled the movement of all produce and related materials (e.g., farm equipment, soil). Furthermore, in collaboration with United States Department of Agriculture (USDA) inspection agencies, seed potato exports to the United States were immediately halted(Spud Smart, 2020).

This rapid response among various agencies and jurisdictions was attributed to the Potato Wart Domestic Long-Term Management Plan, established by Canada in response to the presence of potato wart in Prince Edward Island in 2000, which shut down trade between Canada and the United States and resulted in the loss of $22 million in sales for P.E.I. farmers (CBC News, 2021).

5.1.2 Communication Challenges Among Actors in the Plant Health System

Failures of communication occur when relevant expertise, knowledge, and evidence are not included or shared among those with a part to play in the plant health system, or when relevant federal, provincial and territorial departments and agencies, Indigenous communities, or other key actors are omitted entirely from regulatory and decision-making processes.

Due to issues of jurisdictional control in Canada, it is of particular importance that cross-jurisdictional communication be considered as a protection against potential plant health risks. In forestry, the Canadian Council of Forest Ministers (CCFM) was originally created to foster dialogue among federal, provincial, and territorial governments (CCFM, 2015). The CCFM has noted, however, that success in achieving thriving, healthy, and resilient forests that support a number of ecosystem services will be dependent on collaboration among more actors, including Indigenous Peoples, the forestry sector, NGOs, academia, and individual members of the general public (CCFM, 2019b).

Failure to share emerging research poses a risk to plant health

Among the most significant risks identified by international plant health researchers, including scientists in Canada, is the existence of information silos produced by different actors who fail to connect, or whose research remains unknown to each other without a shared information network (B. Gibbs, personal communication, 2020; Giovani *et al.*, 2020). It can be difficult to gather all the relevant information relating to a particular invasive species, for instance, since work may not be shared among actors, or among different (but related) experts (e.g., weed scientists and ecologists). This lack of communication or shared research networks leads to repetition of work, a lack of a comprehensive approach, and the mismanagement of already scarce research funding (Giovani *et al.*, 2020). Without collaboration, communication, and networks to connect the research and work of academics, governments, NGOs, industry, Indigenous Peoples, and other actors, national plant health systems (such as Canada's) may fail to use all available resources and knowledge to manage and mitigate potential risks as they arise (Giovani *et al.*, 2020).

Collaborative networks to safeguard plant health have already been implemented nationally in some countries, such as New Zealand (B3, 2020). Better Border Biosecurity (B3) is a system that joins researchers, industry, and government to produce and implement the best science and technology to protect New Zealand's plant systems. B3 is designed to share investment and expertise across sectors in order to support the flow of information and to promote effective governance (B3, 2020). As an island nation, New Zealand has a geographic advantage over Canada when it comes to protecting plant health from invasive species; however, its leadership and initiative in the field of plant health research and protection may still provide Canada with a potential framework for collaboration and promising practices.

International researchers have noted that a global phytosanitary research network could align research agendas and accelerate science that supports phytosanitary activities — a potential benefit to all actors in the plant health system, but especially to policymakers (Giovani *et al.*, 2020). Furthermore, as noted by Ristaino *et al.* (2021), the creation of a coordinated and global system for data sharing and disease tracking and reporting could not only help to identify and control emerging plant diseases, but also serve as a useful tool in ensuring global food security. Within Canada, the management of risks to animal health, particularly through the Canadian Animal Health Surveillance System (CAHSS), provides a model for research sharing and network building that could be useful in improving coordination among actors in the Canadian plant health system (Box 5.4).

Box 5.4 Animal Health in Canada — A Model for Research Coordination

Created in 2015, the CAHSS is a network that shares surveillance information and initiatives related to animal health across Canada (CAHSS, 2020c). Its goal is to provide an integrated and collaborative approach that can be responsive and foster open communication across the entire animal health system (CAHSS, 2020a). The CAHSS relies on the participation of federal, provincial, and territorial governments (including representatives from policy areas related to agriculture, animal health, environment, and public health), industry, veterinary associations and their members, as well as other individuals and groups involved in animal health and surveillance (CAHSS, 2020a). Its work is organized and divided by issue (e.g., vector-borne disease network, regional surveillance) and animal type (e.g., beef network, equine network) (CAHSS, 2020c). Each primary network shares information and promising practices at meetings and events, including pan-Canadian roundtables. In addition, information is shared across networks when needed or relevant.

The CAHSS uses the latest data and analysis to remain apprised of potential threats. The most recent data are made accessible to the public online through weekly intelligence reports that detail global outbreaks, alerts, and surveillance initiatives (CAHSS, 2020b). In contrast, a search of the CFIA website conducted in June 2021 revealed a lack of real-time reporting and up-to-date published metrics and indictors, with the most recently published plant protection survey reports being three years out of date (e.g., CFIA, 2019d).

To build upon the strength of research in Canada, the federal government has identified mobilizing a National Plant Health Information Network as a potential tool for collaboration, data sharing, and planning among key partners (CFIA, 2019c). In addition, the Canadian Plant Health Council (2019) identified three priorities in its work plan:

- **Surveillance —** Develop an annual process to harmonize surveillance plans, priorities, and protocols, and share results across Canada.
- **Biosecurity —** Assess uptake and promote awareness of biosecurity tools and programs to improve uptake.
- **Emergency Response —** Identify key contacts and establish a multi-partner communication plan for rapid and effective emergency response.

All three priorities indicated that the most pressing need among key partners is for standard operating procedures across relevant agencies and jurisdictions that embody the values of coordinating surveillance, planning, response, and evaluation (Canadian Plant Health Council, 2019).

By November 2019, the Council had progressed in contacting surveillance practitioners across Canada to identify potential areas of coordination and three pests for targeted action: the European corn borer (*Ostrinia nubilalis*); amaranth (*Amaranthus* sp.); and clubroot (Canadian Plant Health Council, 2020). The Council also conducted a biosecurity scan to identify the types and locations of existing programs, and reviewed existing emergency response programs to identify successful examples. In addition, multiple webinars were held with relevant actors, including members of industry, academia, and government working groups. However, in March 2020, momentum halted when the Council suspended its activities to allow its membership to deal with the impact of the COVID-19 pandemic. Activities were resumed in October 2020, and the Council's work plan was extended an additional year (Canadian Plant Health Council, 2020). The Council, in its work to date, represents one of the most coordinated and thorough efforts in surveillance and coordination of plant health at a pan-Canadian level.

5.2 Surveillance, Monitoring, and Management: The Benefits and Challenges of Innovation

Emerging technologies may hold promise for addressing a suite of plant health risks, notably for the early detection and the precise management of risks. Indeed, technologies such as data analytics, remote sensing, or precision agriculture and forestry may offer potential benefits in managing environmental and ecological challenges, including those from the impacts of climate change (Wolfert *et al.*, 2017; Newman & Fraser, 2021; Ristaino *et al.*, 2021). While these tools and strategies may provide benefits, there are also several challenges preventing their wholesale adoption across sectors in Canada. Among these challenges is a dearth of relevant expertise in big data and analytics to effectively employ these emerging technologies (Steele, 2015) and a lack of policy initiatives to ensure widespread accessibility of new tools for a variety of producers (Bronson, 2018).

Additionally, innovation itself may create foreseen and unforeseen risks (Stilgoe *et al.*, 2013; Barrett & Rose, 2020). For example, the cost of adopting precision agriculture could be an important barrier that can exacerbate inequality (Bronson & Knezevic, 2016; Rose *et al.*, 2016). As reviewed by Barrett and Rose (2020), "[t]echnological advancements may favour the already powerful, such as larger farm businesses over small family farms who have less capacity to invest in new technology." The technological revolution in agriculture can encourage the consolidation of farmlands, which can contribute to other socio-economic and ecological risks related to plant health, such as a reduced interest in farm ecological enhancement (Rotz *et al.*, 2017).

However, technological tools can also be useful in reducing ecological impacts and risks. In some cases the use of biotechnologies has led to a decrease in pesticide use (Zilberman *et al.*, 2018; Brookes & Barfoot, 2020), and the use of digital tools to monitor and identify pests can aid in the more targeted application of pesticides in smaller volumes (Cornell University Cooperative Extension & PES, n.d.). Biotechnologies may also allow for greater productivity on smaller plots of land, thus reducing carbon emissions as well as the overall environmental footprint of agriculture (Zilberman *et al.*, 2018). As noted by Zilberman *et al.* (2018), "[a]gricultural biotechnology is diverse, with many applications having different potential impacts. Its regulation needs to balance benefits and risks for each application."

5.2.1 The Use of Data in the Identification and Management of Plant Health Risks

The use of big data[12] and sophisticated computing to mine these data has a number of applications relevant to plant health, including the potential to help with early risk recognition, alert systems, and monitoring. One emerging tool in sustainable forest management (SFM) is the use of big data to support precision forestry. While precision forestry remains in its early stages, SFM may eventually help to maintain land productivity, and potentially mitigate adverse impacts of climate change (Mansuy, 2016). While precision forestry has the potential to improve risk management in forests, its use in Canada to date has been limited, and it has not significantly changed the ways the country's forests are managed.

12 Big data "is a term that encompasses the use of techniques to capture, process, analyze, and visualize potentially large datasets not accessible to standard IT" (Thomas, 2017). It generally refers to accessing large quantities of digital information, providing an opportunity to advance science and support natural resource management broadly using data-intensive approaches (Hampton *et al.*, 2013).

In contrast, precision agriculture is more widely used, and the data collected can allow for the early detection of pests; differentiation among diseases; identification of pathogens; and the assessment of disease severity (Mahlein, 2016). AAFC is using geospatial data to monitor droughts, measure crop inventory, and track seasonal labour across Canada during the COVID-19 crisis (Ashton & Giroux, 2020; AAFC, 2021a). Indicating its support for the continued adoption of precision agriculture, in 2017, the Government of Canada invested $25 million in agricultural technologies, including precision agriculture methods, that reduce greenhouse gas emissions (AAFC, 2018b).

Challenges in the management and use of big data prevent its full inclusion in risk detection and mitigation

There are several broad cross-sectoral challenges associated with the use of big data that must be addressed before some technologies can be fully incorporated into the plant health system. These include:

- **Inadequate acquisition, processing, integration, and storage of data —** This is both a technical and an economic challenge for many actors, including individual landowners, private companies, and the public sector. Data management requires an investment in both computing power and data, and in computer science expertise. The volume of data that exists is in many cases outpacing capacity for storage and methods of integration (Kaisler *et al.*, 2013; Mansuy, 2016).
- **Concerns related to data security and ownership —** There are unresolved concerns over data ownership and security, especially among farmers (Clapp & Ruder, 2020). While an individual farmer's data may have limited value, it becomes a valuable resource when grouped with the data of other farmers or from a variety of other sources (Wolfert *et al.*, 2017). Some farmers have concerns over data storage and the vulnerability of personal information (e.g., information related to farmers and their staff, property location and features, crop yields). There are also persistent questions relating to data ownership. For example, farmers may not know if they have the rights to information when the data collected are produced on their land but obtained through sensors and other tools that they do not directly own (Haire, 2014; Wolfert *et al.*, 2017).
- **Difficulty in assessing the quality and quantity of some data —** When making multidimensional data part of the decision-making system, there may be challenges in reaching consensus among actors in determining which data are relevant; measuring accuracy and reliability; determining how much data is sufficient; and assessing the value of data related to other inputs in decision-making (Kaisler *et al.*, 2013; Weersink *et al.*, 2018).

Essentially, the data produced will be of little relevance unless they can be effectively managed, and unless actors know what information they want to access and how to best use it. Not all data are useful or robust. Without effective management, or a clear purpose, these data become a glut of information with little relevance (Wolfert *et al.*, 2017). The use of molecular detection in the forestry sector highlights a number of these challenges, including data management and widespread adoption (Box 5.5). In addition to issues surrounding big data, the Panel also notes that, given the complexities in the existing governance system, there are also challenges incorporating and directing small data (those which are accessible, actionable, and come in manageable volumes; Wigmore, 2014) toward the management of plant health risks.

A culture of open data acquisition and sharing may be beneficial to overcoming some of these challenges. Potential ways forward may include harnessing citizen science to crowdsource and verify environmental data collection (McKinley *et al.*, 2015), and encouraging open science (GODAN, n.d.). For instance, according to Mansuy (2016), the Smartforests Canada platform provides "*in situ* real-time measurements of various forest attributes (tree growth, tree characteristics, biodiversity, soil, air, carbon, etc.)"; this platform could be paired with traditional field studies to allow actors to monitor environmental changes and respond to market needs. Mixed (public and private) research ventures, such as Canada's FPInnovations — a collaboration among a research institution, the private sector, and government — may bridge data-sharing challenges by conducting demand-driven applied research for the forestry industry (Mansuy, 2016). In the field of agriculture, the Open Ag Data Alliance provides open source software that ensures farmers own the data produced on their farms (OADA, 2021), while Global Open Data for Agriculture and Nutrition (GODAN) is a Montréal-based, international network of government, NGO, and private partners that advocates for open data (including agricultural, environmental, and socio-economic data), and consults on initiativs that use these data to work toward global food security (GODAN, n.d.).

Box 5.5 Molecular Detection Tools in Forestry

The use of molecular tools to detect and identify non-native forest pathogens was developed as part of the University of British Columbia's TAIGA project (Lamarche *et al.*, 2015). The technology, created with funding from Genome British Columbia (Genome BC, 2021), allows for the creation of rapid and reliable tools capable of detecting minute amounts of target pathogen DNA for potential use by organizations, such as the CFIA (and its international equivalents) and the forestry industry (Lamarche *et al.*, 2015). While the technology has proven feasible and has been recognized as a significant improvement in the field of detection, there are a number of non-technical challenges that may prevent its widespread uptake (Hall *et al.*, 2019).

There are challenges with interpreting and using the vast amount of data produced through molecular detection and diagnostic testing (Hall *et al.,* 2019). These include finding or developing the relevant expertise in data management and analytics, as well as the relevant expertise to provide essential context. As noted by a representative from the field of plant health policy who was interviewed as part of a study on the effectiveness of TAIGA technology, "detecting [the pathogen] is one thing, proving that it's making some harm to the forest is another thing" (quoted in Hall *et al.*, 2019). In addition, there are ongoing concerns regarding how the data may be used. It has been noted that the technology's utility "will thus need to be closely entwined with guidelines, operating procedures, and limitations" (Hall *et al.*, 2019). Other challenges to adoption include the potential impacts of the technology on international trade, such as the misuse of data to create false trade barriers, and the cost of adoption; the latter is of particular concern to a forestry industry that is both cost-sensitive and often reactive rather than proactive in regard to phytosanitary issues (Hall *et al.*, 2019).

A lack of relevant expertise is preventing the widespread uptake of emerging innovations

There is a shortage of technical expertise in both agriculture and forestry. To overcome this challenge, some have recommended attracting and retaining top international talent by way of an expedited visa process; investing in fellowships and exchange programs with leading universities in relevant fields; and broadening the scope of talent to attract expertise from related fields (e.g., health and life sciences, data analytics) (Advisory Council on Economic Growth, 2017).

Evidence also suggests there is a gap between the need for labour and labour supply (Ontario Agricultural College, 2017; Rotz *et al.*, 2019). The adoption of precision agriculture, for example, requires advanced skills in several areas, including robotics, computer programming, software systems, and agronomy. Canada's colleges and universities have limited programs equipped to train students in these fields or have had recruitment outpaced by the demand to fill these roles (Ontario Agricultural College, 2017; Rotz *et al.*, 2019). However, there is ongoing effort to meet this demand. For example, the Agricultural Technology programs at Olds College in Alberta offer up a model for skills development in a timely manner, which can in turn quickly provide some of the expertise needed in the field (Box 5.6).

Box 5.6 The Precision Agriculture-Techgronomy Program at Olds College

The Precision Agriculture-Techgronomy program at Olds College in Alberta is a two-year diploma designed to further the education of students with existing degrees in fields such as agriculture, engineering, mechanics, and environmental sciences (Olds College, n.d.). Working on an on-site 746 ha ecosystem called the Smart Farm, students are trained in the latest technologies employed across the agricultural industry (Olds College, 2021). Specific areas of training include automation and robotics; data collection, management, and utilization; technology development; and regenerative agriculture. The Smart Farm was designed to be a space for collaboration and learning among students, faculty, producers, and industry (Olds College, 2021).

In addition to the expertise needed to design and operate new technologies and to analyze data, there is an accompanying need to support and train farmers who may choose to more fully integrate digital technology into their operations. This includes support for how to use, program, maintain, and fix systems and newly available tools (Weersink *et al.*, 2018; Rotz *et al.*, 2019). In some cases, farmers are taking the initiative themselves through participation in online platforms such as Farm Hack, which allows farmers from around the world to connect and share their experiences in maintaining, building, and repairing farm tools, including digital technologies and software (Clapp & Ruder, 2020; Farm Hack, n.d.). There are concerns that training may not be accessible to all, due to cost, availability, or other limitations; therefore the adoption of emerging technologies by some may exacerbate existing inequalities among producers (Bronson & Knezevic, 2016; Rose *et al.*, 2016).

Broad approaches to innovation can result in novel approaches to overcoming plant health risks

Advancing innovations in plant health to meet future risks is not simply a matter of focusing on digital technologies to improve resilience. To deal with risks that may be associated with the adoption of precision agriculture, some have suggested that policymakers support a diversity of farmers operating at various scales and strategies to engage with new technologies (Bronson, 2018; Barrett & Rose, 2020). A diversity of farm types can provide a variety of benefits for Canada's ecosystems and consumers. While large-scale farms may have the economic means to implement innovations that may increase crop yields or offer other advantages, small- and medium-scale farms may be particularly adaptable to new market opportunities and changing environmental conditions (ACT, 2013; Small Scale Food Manitoba Working Group, 2015; Pollan, 2021). Interviews with farmers indicate that investing heavily in digital strategies for farming may not be the only or even the best strategy (Barrett & Rose, 2020). It has been argued that the prioritization of new technologies often comes at the expense of the development and refinement of other strategies, such as farmer-led innovations, improved communications, and use of existing technologies (Barrett & Rose, 2020). Furthermore, Bragdon and Smith (2015) note that "[t]here has been relatively little inquiry into how innovation platforms support farmer-led innovation." To help overcome this, they suggest that "[f]irst and foremost, agricultural research institutions and organizations must recognize farmers as innovators rather than solely recipients of research results" (Bragdon & Smith, 2015). While there has traditionally been a power imbalance that has relied on knowledge derived from academia and western-based science to guide policy decisions on plant health management, more recently, research has been directed toward recognizing and implementing Indigenous and farmer-led knowledge, which has supported plant health in communities across the globe for centuries (e.g., Hill *et al.*, 2019). The challenge lies in braiding together broad scientific principles with site-specific knowledge (Duru *et al.*, 2015; Hill *et al.*, 2019; Lima, 2019).

The application of agroecological principles to farming has proven valuable when applied either in isolation or in partnership with precision agriculture. Agroecology aims to support diversification and multi-ecosystem benefits, including food production, while also mitigating negative environmental or social impacts associated with some farming methods (Isaac *et al.*, 2018). Examples of agroecology include common Canadian practices such as intercropping, cover cropping, and extended crop rotations, but also less common practices such as cycling nutrients on-farm and abstaining from the use of pesticides (Isaac *et al.*, 2018). While there is no systemic survey of the use of agroecological practices in Canada, existing evidence indicates that their presence is limited, and that research funding opportunities that encourage basic research into the field have been limited (Isaac *et al.*, 2018; SCAAF, 2018). However, an analysis of Tri-Agency funding grants, and those provided by farm organizations (e.g., EFAO, n.d.-b) and other provincial and federal programs, including the recently created Living Laboratories Initiative (Box 5.7), suggest there may be a growing interest in the field (Isaac *et al.*, 2018; Laforge *et al.*, 2018). Knowledge transfer of agroecological practices has also been facilitated in part through the work of NGOs (e.g., SeedChange, 2021; Young Agrarians, 2021; EFAO, n.d.-a). While these programs have been effective, like most NGO programs, they are susceptible to limited and inconsistent funding (Isaac *et al.*, 2018).

Box 5.7 The Living Laboratories Initiative

The Living Laboratories Initiative is a collaborative approach to the development and adoption of localized and sustainable solutions to address environmental issues faced by Canadian farmers (AAFC, 2021c). Projects directed through Living Laboratories occur in regional hubs where, in an initial phase, farmers collaborate with scientists and other actors to identify their specific needs, and teams share data and ideas. During a second project phase, potential solutions are tested in the field and evaluated based on both scientific research and the experiences of the farmers themselves. Innovations are amended as required and may change to adapt to environmental needs. As noted by AAFC (2021c), "[b]ecause the resulting innovations are co-developed with farmers from beginning to end, they are more likely to be adopted by farmers. The co-development process ensures that innovations are economically viable, technically feasible and desirable for the producers in addition to being scientifically sound." It is anticipated that this initiative will develop practices that assist farmers in responding to the impacts of climate change, while reducing water contamination, improving soil quality, and increasing habitats and biodiversity in farm landscapes (AAFC, 2021c).

5.3 Public Engagement in the Management of Plant Health Risks

With respect to plant health risks, public engagement can help in the surveillance of plants, pests, and the surrounding environment, thereby tracking risks through time. This is an essential component in enacting effective policy changes that have an impact on the ability to prevent, manage, and adapt to evolving plant health risks. Beyond support, public engagement that precedes policymaking can be important in assessing plant health risks, improving public understanding of policy decisions and impacts, and in creating effective policies that are viewed as legitimate by the public (Findlater *et al.*, 2020). The role of the public, however, must also be assessed against potential risks or barriers, including conflicts in values and variable tolerance to risk; existing public knowledge and relationships with plant health systems; and the efficacy of education and outreach programs related to plant health (European and Mediterranean Plant Protection Organization, 2019).

5.3.1 Public Surveillance of Plant Health Risks

The public can be a valuable asset in identifying and mitigating risks to plant health

The public has the power to effect meaningful change in plant health. To create wider awareness of the full breadth of issues, and of the individual's power to influence policy, Pautasso *et al.* (2012) recommend reconnecting the public with their local environments. Generally, many people in Canada could be described as disconnected from the local ecology that surrounds them (NCC, 2018). Without an existing relationship with their environment, the average person is ill prepared to recognize or manage plant health risks as they occur. Organizations such as the Canadian Council on Invasive Species seek to connect members of the public with professionals in order to train them to recognize invasive species in their own environment and limit potential social, environmental, and economic impacts (CCIS, 2014).

In drafting European standards for public awareness campaigns on plant health, the authors noted that, "[i]n principle, public awareness can create a large number of 'citizen scientists' who become interested in plant health and who are then more likely to see an outbreak in its early stages than inspectors are during official surveys, which are necessarily limited by available resources" (European and Mediterranean Plant Protection Organization, 2019). It is therefore a benefit to have members of the public be well informed about general plant health risks, and it can be especially useful during campaigns to target specific risks. Within Canada, there are a number of ongoing citizen-science projects in the field of plant health. Examples include the Budworm Tracker Program (BTP), which asks volunteers to monitor and report the incidence of spruce budworm moth populations throughout forests in eastern Canada, and the Early Detection & Rapid Response (EDRR) Network of Ontario, which trains individuals to recognize invasive species within their communities and to report sightings (GC, 2020). In addition, iNaturalist.org is a repository of all types of citizen science projects and observations, including many relating to plant health, such as the Eastern Hemlock Project, which monitors the plant's spread throughout eastern North America, and another project dedicated to recording sightings of invasive species in Ontario (iNaturalist.org, n.d.-a, n.d.-b).

The European and Mediterranean Plant Protection Organization (2019) provides criteria to help determine whether calling on the public to help with local invasive species has the potential for a positive impact. These include consideration of transmission pathways, ease of detection, and ease of management, eradication, or containment. Awareness campaigns are beneficial in cases where pests are easily identified, and early detection could lead to eradication. On the other hand, public awareness campaigns could backfire when pests closely resemble native species, when untrained individuals inadvertently spread a pest through negligence or ignorance, or when costs of awareness campaigns outweigh the overall benefits (European and Mediterranean Plant Protection Organization, 2019). With citizen science, additional caution must be exercised with datasets in order to account for errors, uneven sampling, or biases introduced by individuals by chance or by those with a particular agenda (Kremen *et al.*, 2011; Tiago *et al.*, 2017; Irwin, 2018).

There are existing examples of public monitoring of plant health risks

In the monitoring of risks to plant health, actors can draw from a number of existing models involving key players outside of the governance system. For example, historically, extension services — which assist farmers through communication and education programs in the field — have offered opportunities for growers to share reports of pests, diseases, or other issues (Milburn *et al.*, 2010). These reports helped verify areas of concern, while extension officers provided information to landowners — an important source of knowledge transfer. While extension services used to exist across Canada, a variety of factors, including a lack of political support, have led to their discontinuation in some provinces and territories; in other cases, they have been replaced by online communications to relay information to farmers (Milburn *et al.*, 2010). In provinces where they continue to exist, extension services have adapted and continue to provide essential, on-the-ground services. For example, in Saskatchewan, provincial plant disease experts and crops extension specialists have partnered with grower associations in an effort to test and monitor for pests and diseases, including clubroot (Gov. of SK, 2021b; SaskCanola, n.d.). In 2020, a partnership between SaskCanola and the Government of Saskatchewan resulted in the inspection of over 966 fields through the distribution and testing of soil monitoring kits and the continued surveillance of infected areas by provincial pest control officers (Gov. of SK, 2021b). In addition, the Prairie Pest Monitoring Network (PPMN) brings together entomologists who conduct research and monitor and inspect for pest populations among field crops in the Canadian Prairies. This research helps inform growers of potential pest risks for specific crops. PPMN activities are also coordinated among government (federal and provincial), industry, and academic actors (PPMN, 2021).

5.3.2 Public Support and Understanding of Plant Health Risks and Management Policies

Public acceptance of risk is variable and can be informed by one's values

The diversity of values across actors in the plant health system and the public at large contributes to differences in the understanding of plant health, resulting in divergent opinions on how risks ought to be identified and managed. Risk tolerance associated with innovations used to manage plant health, for example, has been shown to be variable; in the case of biotechnology in agriculture and forestry, some studies show high public concern, others show support, and others simply indicate a lack of understanding of what biotechnology is (reviewed in Hajjar *et al.*, 2014). Hajjar *et al.* (2014) suggest that to truly engage the public on the question of using biotechnology in forestry, there must be a greater understanding that begins with defining the terms of reference themselves and describing the technologies and any potential outcomes they may lead to.

These discussions cannot be separated from cultural and personal values. For example, what is it that the public values most about forests? Is it aesthetics? Economic contribution? Forest health? Traditional ways of life? Each of these values may necessitate different preventative and management practices, and influence policymaking in unique ways (Hajjar *et al.*, 2014). Based on the multitude of cultural values associated with forests in Canada, it is likely that the use of biotechnologies will be a growing source of public concern. It has been suggested that scientists and policymakers would do well to incorporate broader perspectives and seek the input of the social sciences and humanities when considering the potential benefits and risks of using biotechnologies to manage pests and disease in plant health systems, and as a method to adapt plants to withstand climate variability — whether that be in forestry or among agricultural plants (Pelai *et al.*, 2020). There is recognition of the importance of broader perspectives in drafting environmental policy in Canada. The 2019 *Impact Assessment Act* commits the Government of Canada to sustainable approaches, and to integrating public participation, science, and Indigenous knowledge in the development of major projects (GC, 2019d).

Science communication and engagement can be effective in fostering public understanding of risks to plant health

Low public trust in government has been linked to low public support for environmental policies, including those related to climate change and forestry management (Peterson St-Laurent *et al.*, 2019). While science skepticism remains a persistent and troubling issue, public trust in scientists is generally high (Peterson St-Laurent *et al.*, 2019). At the same time, studies have shown that public trust is earned not just through evidence-based arguments, but also by engaging the public in a transparent way about science early in the decision-making process (Sheppard, 2005; Peterson St-Laurent *et al.*, 2018b, 2019).

A review by Peterson St-Laurent *et al.* (2019) found that the *knowledge deficit model*, which "holds that resistance to science and technologically-based management solutions originates from a lack of familiarity and information," has proven faulty. Studies focusing on education and science literacy related to several controversial topics, including climate change, have resulted in even highly science-educated participants selecting evidence to support already established conclusions (Peterson St-Laurent *et al.*, 2019). Some studies show public opinion is more strongly tied to existing cultural values, social identity, and political and religious beliefs, as opposed to one's knowledge or education (Braman *et al.*, 2012). Bronson (2019) notes the inadequacy of the knowledge deficit model in relation to groups of Saskatchewan farmers concerned with regulatory measures and research priorities surrounding biotechnologies. Their resistance to biotechnologies stemmed not from a lack of scientific understanding, but from broader concerns related to justice, power, and — perhaps most importantly — approaches to risk characterization that differ from the technical framework used by the Government of Canada (Bronson, 2019).

The source of information has also been shown to be a factor in establishing public trust. A recent study of public trust in scientists by the Pew Research Center found that respondents held generally positive views of scientists, with 51% noting that they had "a great deal of confidence in scientists to act in the best interests of the public," while a further 35% indicated that they had a fair amount of confidence for the same (Funk *et al.*, 2019). Fifty-eight percent of respondents felt that industry-funded research made them trust the results less, while 57% noted that they trusted findings more in cases where the research was publicly available and independently vetted (Funk *et al.*, 2019). In response to public views on science, and in an effort to find ways to combat online misinformation, the Government of Canada — in advance of the International Year of Plant Health in 2020 — articulated a goal of engaging the public by including plant health science, resource management, and risks (especially climate change) as key themes at all education levels, and by finding novel ways to build trust and improve science communication among the general public (CFIA, 2019c).

Creating policies and implementing new technologies in the face of diverse values and risks can be daunting; however, potential risks can be mitigated through early public engagement (Findlater *et al.*, 2020). Engagement with diverse actors should be meaningful and allow time for true participation and deliberation (Walker & Daniels, 2019). It can begin as early as including the public in the formation of questions and extend into other participatory methods, including participatory budgeting (Participatory Budgeting Project, n.d.). Actors are more inclined to trust efforts when they feel their input is valued and used in decision-making (Walker & Daniels, 2019). Conversely, trust is lost when they feel that input is solicited for appearances and not actually considered or incorporated into decisions (Irvin & Stansbury, 2004; Nelson *et al.*, 2017). The purpose of engagement is not to rally support around an already decided policy; instead, it should be recognized that "[t]he public is a powerful force; through transparent and meaningful engagement, the likelihood of achieving consensus-based solutions is increased" (Hajjar *et al.*, 2014). Participation can be especially useful in the current climate of misinformation and siloed information, since these factors have "the potential to generate public confusion" and "act as a deterrent to effective decision making" (Peterson St-Laurent *et al.*, 2019).

6

Indigenous Peoples' Rights and Roles in Plant Health

Chapter Findings

- Despite Indigenous rights to access, manage, and govern land in Canada, there is limited engagement with Indigenous Peoples by government departments responsible for managing and promoting plant health.
- Reciprocity and responsibility are integral components of Indigenous worldviews and legal traditions, which demonstrate a respect for the land reciprocated by future abundance. Plant health in Canada could be strengthened by including Indigenous approaches to ecosystem management.
- Indigenous knowledge includes long-term ecological and environmental data on animal and plant life and provides insight into how ecosystems have changed over time. The loss of Indigenous knowledge and the lack of its inclusion in decision-making processes are risks to plant health and to Indigenous rights.
- Including Indigenous knowledge systems can contribute to the management of plant health risks if shared in an ethical space, where all cultural perspectives are examined simultaneously and collaboratively, and where they are given equal consideration in questions of plant health.

There is a deep and longstanding relationship between Indigenous Peoples and plant life. Indigenous Peoples in Canada and elsewhere often consider humans to be elements of nature, where reciprocal exchanges between humans and non-humans nurture co-production, and where local communities manage, conserve, and are part of ecosystems (Oberndorfer *et al.*, 2017; IPBES, 2019b). The Syilx Okanagan People in British Columbia practise a model of regenerative harvesting in which large seasonal gardens are tended through traditional methods that have been refined over centuries and regulated by recognized authorities in the community (Armstrong, 2020). The importance of reciprocity in plant-human relationships is recognized explicitly; for example, Haudenosaunee environmental philosophy emphasizes the responsibility of people to respect and live in harmony with nature (Alfred, 2007). Similar duties to protect and nurture plant life are evident among other Indigenous cultures, where the generosity of plants is recognized and reciprocated through acts of care and gratitude (e.g., Kimmerer, 2013; Armstrong, 2020; Mills, 2020). The importance of plants is articulated by Mary B. Andersen from Makkovik, an Inuit community in Nunatsiavut (Labrador):

> *Plants give us everything: food, shelter, well-being, heat. They protect the soil from erosion. All medicines come from plants, even if people think they're made somewhere. That understanding is getting lost now. You don't realize it until you think about it how much we depend on plants. It would be pretty bleak if you never had plants. Plants are so important in the food chain. Without plants, what would we have? We wouldn't have very much.*
>
> Quoted in Oberndorfer *et al.* (2017)

Indigenous worldviews, values, and management systems often emphasize multiple ecosystem functions and uses, resulting in diverse landscapes (Berkes & Davidson-Hunt, 2006), interconnectedness among living beings (Castleden *et al.*, 2009), an ethic of reciprocity (Kimmerer, 2013), and a spiritual relationship with the land (Booth & Skelton, 2011). In contrast, the non-Indigenous management paradigm that currently governs most managed landscapes in Canada tends to focus on a single dominant value (i.e., economic value), which prioritizes commercially valuable plant species (e.g., timber-producing trees) over other ecosystem functions (e.g., non-timber forest products, or plants without direct commercial value) (Berkes & Davidson-Hunt, 2006; Teitelbaum & Bullock, 2012). Prioritizing timber production can impact the ability of Indigenous people to access and tend to traditional plant foods, materials, and medicines, either through direct exclusion or because management activities, such as aerial spraying and logging, have damaged those plants (Booth & Skelton, 2011; Stolz, 2018). The relationships between Indigenous people and plant health have been and continue to be integral to Indigenous identity, culture, and food security. The loss of Indigenous plant knowledge and management practices can be viewed as both a risk to plant health in Canada as well as an infringement on Indigenous rights.

6.1 Indigenous Rights Relating to Land Access, Management, and Governance

Indigenous Peoples in Canada, which include First Nations, Inuit, and Métis Peoples, are prominent rights-holders in relation to land and plants. Indigenous governments, which exist in different forms in Canada, have some control over land and resources, with differing rights and responsibilities depending on the mechanisms of authority and the nature or lack of agreements with the Crown. These rights are rooted in Indigenous Peoples' prior occupation of North America, the *Royal Proclamation of 1763*, the *Constitution Acts, 1867 to 1982* (originally the *British North America Act of 1867*), and various historical and modern treaties (RCAP, 1996; TRC, 2015). Indigenous Peoples have specified use rights to certain territories recognized by the Government of Canada in the original (numbered) treaties and territories negotiated as part of modern land claim agreements (JUS, 2018).

Treaty and Indigenous rights (including land claims and self-government agreements) may provide for a range of access to, and some control over, resources and land traditionally occupied by Indigenous Peoples (CIRNAC, 2020), such as plant gathering rights (CIRNAC, 2016).

Aboriginal title provides the inherent right to use, control, and benefit from traditional land

In unceded territories where there is no treaty (historic or modern), court cases in Canada have affirmed the continued existence of Aboriginal title — an inherent right to use, control, and benefit from traditional lands or territories (SCC, 1997, 2014; JUS, 2018). Aboriginal title rights are inherent, and separate from rights afforded to non-Indigenous Canadians under common law, reflecting the occupation and relationship between Indigenous people and their home territories prior to contact (Hanson, 2009). In 2014, the Supreme Court of Canada for the first time established and declared Aboriginal title to the Tŝilhqot'in First Nation in a specific area of 190,000 ha in British Columbia (SCC, 2014; Tŝilhqot'in National Government, 2021). The court case was initiated after six bands within the Tŝilhqot'in First Nation opposed the granting of a commercial logging licence to the Government of British Columbia on their traditional territory (SCC, 2014). In practice, any timber on this title area is owned by the Tŝilhqot'in First Nation (as opposed to the Crown), which prevents the provincial government from authorizing timber harvesting to forestry companies on this land (Tŝilhqot'in National Government, 2021).

The Crown is required to consult with Indigenous people on decisions that may affect land on which Aboriginal title is asserted (i.e., never extinguished), even if it is not yet formally established (SCC, 2014). However, title is not absolute. Development projects can still proceed on that land so long as it occurs with the consent of title-holders; barring that, governments must prove that the development is "justified on the basis of a compelling and substantial public interest," and that fiduciary duty toward Indigenous land-holders has been met (SCC, 2014).

The current definition of Aboriginal title, which resulted from multiple court cases, provides some clarity to legal proceedings; however, it may differ from some Indigenous people's understandings of title (Hanson, 2009). For example, some Indigenous people do not accept that the Crown has an underlying title to what is now known as Canada, and question the legitimacy of the Crown's assertion of sovereignty over this land (McCrossan & Ladner, 2016; GC, 2017; JUS, 2018). Similarly, broader ideas of imposed private property may be incompatible with some Indigenous legal traditions and philosophies (GC, 2017).

Federal, provincial, and territorial governments have a duty to consult and accommodate Indigenous Peoples

In keeping with Section 35 of the *Constitution Act* (1982) to recognize Indigenous and treaty rights, the Supreme Court of Canada has affirmed that federal, provincial, and territorial governments have a duty to consult and accommodate Indigenous people when undertaking actions that may impact these rights (SCC, 2004, 2010, 2014; Brideau, 2019).

Land rights require that provincial, territorial, and federal governments carry out consultation and, if required, accommodation, if Indigenous and treaty rights may be infringed on by proposed development or policies. In some cases, depending on the strength of both Indigenous claims and potential infringement of rights, governments may be required to obtain consent from relevant Indigenous rights-holders when managing and using these lands (JUS, 2018; Brideau, 2019). The standard to secure consent from Indigenous people is "strongest in the case of Aboriginal title lands" (JUS, 2018). While the Government of Canada recognizes the principles of engagement with Indigenous people, and "aims to secure their free, prior, and informed consent" when it pertains to the use of Indigenous lands and resources, this consent is not required in all cases of land use or disruption (JUS, 2018). In addition to the rights described above, Indigenous governments and other orders of government may enact bylaws related to the environment on federal Indian Reserve lands under the *Indian Act* or self-governing agreements (JUS, 1985; GC, 2010).

International declarations and conventions endorsed by Canada recognize the rights of Indigenous Peoples

Internationally, Indigenous rights are recognized in the *United Nations Declaration on the Rights of Indigenous Peoples* (UNDRIP), which includes provisions related to land use, resources, and access to traditional medicinal plants (Articles 24, 25, and 26) (UN, 2007). The Government of Canada endorsed UNDRIP in 2010 after initially opposing its passing in 2007 (Hill, 2016). In 2016, the federal Liberal government stated its support, "without qualification," for UNDRIP (INAC, 2016) and, in 2021, enacted legislation, known as *An Act Respecting the United Nations Declaration on the Rights of Indigenous Peoples*, aimed at ensuring that Canada's laws are in line with UNDRIP (GC, 2021b). However, some Indigenous groups are concerned that the *Act* contains too few details on how Canadian legislation would change in light of UNDRIP (McIvor, 2020), with one nation in particular — the Kitchenuhmaykoosib Inninuwug First Nation in northwestern Ontario — objecting to the bill's premise that Canada has ownership over the land as part of a contested historical Doctrine of Discovery (Turner, 2021).

The *United Nations Convention on Biological Diversity* (CBD), to which Canada is a signatory, recognizes "the close and traditional dependence of many indigenous and local communities embodying traditional lifestyles on biological resources, and the desirability of sharing equitably benefits arising from the use of traditional knowledge, innovations and practices relevant to the conservation of biological diversity and the sustainable use of its components" (UN, 1992). Further, the CBD notes that member nations should, "[s]ubject to its national legislation, respect, preserve and maintain knowledge, innovations and practices of [I]ndigenous and local communities embodying traditional lifestyles relevant for the conservation and sustainable use of biological diversity and promote their wider application with the approval and involvement of the holders of such knowledge" (UN, 1992).

Indigenous legal traditions lay out the responsibilities and relationships between the land and people

Indigenous societies in Canada practise legal traditions that reflect their needs to manage and govern resources and relationships (Curran & Napoleon, 2020), creating expectations about proper conduct (Borrows, 2005). Indigenous legal traditions are evident historically in treaty and marriage relationships, such as the Great Law of Peace among the confederacy of the Cayuga, Mohawk, Oneida, Onondaga, Seneca, and Tuscarora nations (Borrows, 2005). In relation to plant health, Indigenous legal traditions can include guidance for cultivation practices of selective harvesting, pruning, soil aeration, and planting (among others) that demonstrate a respect for the plants, which is reciprocated by future abundance (Deur & James Jr., 2020). The *Great Bear Rainforest Agreements* in British Columbia provide an example of how land-use management can express Indigenous legal traditions regarding relationships between plants and people into colonial law, through a form of protected area management approach called *conservancies* (Curran, 2017). These agreements establish legal standards for government decision-making, through land-use plans and ecosystem-based objectives, that respect Indigenous rights and relationships (Curran & Napoleon, 2020).

Indigenous knowledge is "a broad concept that encompasses the diverse cultures, traditions, languages, geography, and heritage of Indigenous peoples in Canada" (Buck, 2019).

6.2 Indigenous Knowledge Systems and Land Management Practices

Indigenous management and stewardship of plants has occurred for thousands of years around the world and across the land now recognized as Canada, which has allowed for the accumulation of knowledge across time. Plants have been integral to the lives of Indigenous people in Canada since time immemorial and continue to be today (Turner *et al.*, 2012; Kimmerer, 2013). As Turner *et al.* (2020) state, "the biological character and diversity of North America bears the indelible imprint of long-term Indigenous management and stewardship." This was not recognized until recently by descendants of settlers, as the Europeans saw North America as a "wild" rather than a purposefully shaped landscape (Deur & James Jr., 2020; Grenz, 2020). Over the past centuries, as Indigenous Peoples have been displaced from their traditional territories, there has been a number of associated environmental impacts on plant communities, including an overall reduction in biological diversity and resilience, and a heightened risk of forest fires (e.g., as a result of banning traditional landscape burning) (Deur & James Jr., 2020).

6.2.1 Indigenous Knowledge and the Identification of Plant Health Risks

Indigenous knowledge includes ecological and environmental data on animal and plant life and provides insight into how ecosystems have changed over time. Indigenous knowledge of ecosystems is invaluable as it relates to changes in weather patterns; plants' abundance, distribution, and seasonal development; and how these changes impact soils and other ecosystems (Turner & Clifton, 2009).

Indigenous knowledge encompasses multiple ecosystem functions

Indigenous knowledge considers ecosystems not only through provisioning roles (e.g., to provide food, materials, or medicines), but also in cultural and regulating roles. It evolves alongside ecological and social systems, thereby providing insight on how to deal with stressors and sustain ecosystem functions when there is uncertainty and change (Berkes & Turner, 2006; Gómez-Baggethun *et al.*, 2013). The Shoal Lake Anishinaabe community in northwestern Ontario, for instance, has used low-intensity prescribed fires to start ecological processes that facilitate the provision of food (e.g., berries that grow post-fire) and enhance biodiversity in the boreal forest by maintaining a variety of successional stages (Berkes & Davidson-Hunt, 2006). These traditional practices complement the periodic, naturally occurring fires in the boreal forest — an ecosystem driven by disturbances such as fire to renew itself. Periodic, low-intensity fires also help protect the landscape from more severe fires as they create natural fire breaks and reduce fuel accumulation (Berkes & Davidson-Hunt, 2006). There are many other examples of Indigenous fire management elsewhere in the boreal forest (Miller *et al.*, 2010), as well as in British Columbia forests (Lewis *et al.*, 2018).

Indigenous knowledge offers insights into how plants adapt to environmental change

Indigenous Peoples across Canada have responded and adapted to environmental changes for millennia (Turner & Clifton, 2009; Lepofsky *et al.*, 2020). Knowledge is accumulated over the course of multiple generations, so it is especially useful in understanding local changes through time (Turner & Spalding, 2013). The rich contributions of Indigenous people to better understanding, monitoring, and managing the effects of climate change on plants are well documented (Turner & Clifton, 2009; Elk & Baker, 2020; NRCan, 2020k). For example, traditional phenological knowledge relates to "traditional knowledge of seasonal timing of growth, development, reproduction and migration of organisms, which generally occurs in a predictable sequence based on temperature thresholds, length of daylight, moisture or other environmental determinants" (Turner & Clifton, 2009). Especially relevant in a changing climate, knowledge of the expected rate of variation in species abundance and productivity helps communities predict trends (Turner & Clifton, 2009; Hill *et al.*, 2020). Community responses to environmental change at the local level can thus be informed by experiential knowledge of adaptation strategies (Gómez-Baggethun *et al.*, 2013).

Monitoring by Indigenous and local communities can be an important source for both baseline and long-term data on the status of plant health in ecosystems (Turner & Clifton, 2009). For example, the Syilx Okanagan People have identified several *chief species*, some of which are plants, including bitter root (*Lewisia rediviva*) and Saskatoon berry (*Amelanchier alnifolia*) (Terbasket & Shields, 2019). The concept of chief species is similar to that of *keystone species* in ecology, where the activities and abundance of a particular species have an oversized impact on community stability when compared to other local species (Paine, 1969). Due to their important role in the ecosystem, chief species are monitored through time by the Syilx Okanagan People to maintain their reciprocal relationship (J. Armstrong, personal communication, 2020). The Okanagan Nation Alliance is bringing collective knowledge together, such as data on the monitoring of these chief species; this in turn encourages a central repository of knowledge (ONA, 2017; J. Armstrong, personal communication, 2020).

The loss of Indigenous knowledge is a risk to plant health and to Indigenous rights

Indigenous knowledge, and ethnobotanical knowledge specifically, is being lost in Canada (Turner & Turner, 2008) and globally (Gómez-Baggethun *et al.*, 2013). The reasons for this knowledge loss are multifaceted, but fundamentally reflect a failure to protect Indigenous rights and land uses (UN, 2007; Turner & Turner, 2008; TRC, 2015). More specifically, knowledge loss in Canada stems from legacies of forced adoption of non-Indigenous knowledge systems, the impact of residential schooling, the loss of Indigenous languages, decreased engagement with traditional practices, and restricted access to land, including natural resources and land-use changes (Turner & Turner, 2008; TRC, 2015). Threats to Indigenous knowledge have repercussions for plant health in Canada, as Indigenous people's application of traditional knowledge to manage and care for plant species has helped conserve ecosystems (Downing & Cuerrier, 2011). Because much Indigenous knowledge is the result of long-term observation at a local scale, as well as learnings from changes and crises, once it is lost it may be impossible to restore in the short or medium term, resulting in fewer known strategies and their relative effectiveness in responding to climate change and disturbance (Gómez-Baggethun *et al.*, 2013).

The loss of Indigenous knowledge can be viewed as an infringement on Indigenous rights (UN, 2007); in some cases, it is associated with lack of access to, or engagement with, traditional lands. There is a growing concern that disconnection from the natural environment heightens risks to both plant and human health, as Indigenous people become increasingly removed from traditional and local knowledge of plants (i.e., their names and stories) (Armstrong, 2020; H. Lickers, personal communication, 2020), and while they remain under-represented in the agricultural sector (e.g., CAHRC, 2019). This disconnection between Indigenous Peoples and their lands, brought on by colonization and continued marginalization, has made it difficult (and in some cases impossible) for communities to maintain Indigenous knowledge (Wilson, 2004; UN, 2019). For example, declining access to traditional foods has led not only to changes in diet, but to a lack of generational transmission of cultural food gathering and preparation practices (Shukla *et al.*, 2019). In displacing Indigenous communities from traditional lands, there are also lost opportunities to develop vital new knowledge. However, community-led efforts are underway to counter this loss in some Indigenous communities and to revitalize Indigenous knowledge (Coté, 2016), including plant-specific knowledge (Box 6.1). Indigenous communities are working to remedy generational knowledge gaps in the last decade, while providing youth opportunities to use and generate new knowledge (Rutgers, 2021).

Box 6.1 The Lekwungen Community Tool Shed

Metulia (Victoria) in today's British Columbia sits on the ancestral lands of the Lekwungen and Wyomilth Peoples of the Songhees and Esquimalt First Nations (Songhees Nation, 2021). Dating back centuries, these Nations have managed these lands and relied on qwlháal bulbs (camas, *Camassia quamash*), which grew in the oak savannahs of the area. While these Nations once harvested, cooked, ate, celebrated, and traded this traditional food, the presence of the plant dramatically decreased due to colonial land policies and the arrival of invasive species, including Scotch broom (*Cytisus scoparius*), English ivy (*Hedera helix*), and non-native grasses (Turner & Clifton, 2009).

In 2009, the Lekwungen Community Tool Shed (CTS) was created by Cheryl Bryce, an activist from the Songhees First Nation, to revitalize both the growth of qwlháal and the community's cultural traditions (Corntassel, 2020). The Lekwungen CTS meets monthly in local parks and on reserve lands in order to remove invasive species and encourage bulb growth. As was done traditionally, women lead the harvesting, and many women include their daughters in the meetups. CTS members do not ask permission to weed in public spaces, but instead derive their authority from ancestors who managed these lands for centuries. The weed pulls and harvesting have not only increased the abundance of qwlháal but have created opportunities for intergenerational learning and the transmission of traditional and local knowledge (Corntassel, 2020).

Existing risks to plant health and to the environment more broadly are also contributing to the loss of Indigenous knowledge. Some Indigenous knowledge-holders stress that climate change is making it more difficult to preserve and apply Indigenous knowledge, particularly when environmental changes occur rapidly (Downing & Cuerrier, 2011). There are also examples of Indigenous knowledge that is not only persisting but adapting to contemporary conditions (e.g., Gomez-Baggethun *et al.*, 2010; Rutgers, 2021). It is important, therefore, to view Indigenous knowledge as a dynamic knowledge base (Gómez-Baggethun *et al.*, 2013).

Indigenous-led monitoring can be part of a robust plant health protection and management system

Environmental monitoring is not a new practice among Indigenous people, and other monitoring programs are increasingly including Indigenous people in order to draw on their knowledge to better understand ecosystems (Thompson *et al.*, 2019; Reed *et al.*, 2020; Henri *et al.*, 2021). However, in many of these instances, Indigenous people are treated as stakeholders who bring forward important knowledge but who lack influence in decision-making (Reed *et al.*, 2020). One way to include Indigenous-led decision-making into wider plant health policy is to support and involve Indigenous Guardian programs. These programs have recently been implemented in Canada, Australia, New Zealand, and the United States and have emerged as an approach to collaborative environmental governance with Indigenous governments. Importantly, in these programs, Indigenous Guardians act as environmental stewards responsible for multiple functions, including designing land-use management plans, sharing knowledge inter-generationally, and land monitoring (Reed *et al.*, 2020).

The Indigenous Leadership Initiative has been working with partners to build a pan-Canadian Indigenous Guardians network (ILI, n.d.). In this approach, Indigenous Guardians "help Indigenous Nations honour the cultural responsibility to care for land and waters. They serve as the 'eyes and ears' on traditional territories" (ILI, n.d.). Guardians are trained experts who manage protected areas, restore plants, test the quality of water, monitor development activities, and co-create land-use plans. The Guardians network is Indigenous-led and encourages collaboration among Indigenous, federal, provincial, and territorial governments (ILI, n.d.). The seed funding for the initiative was provided in the 2018 federal budget, which allotted $25 million over four years, with the intention of informing a long-term approach for a pan-Canadian program (ECCC, 2020c). There are approximately 70 Indigenous Guardian programs operating across Canada, from Labrador to British Columbia (ILI, n.d.). In 2019-2020, the Pimachiowin Aki Guardians Network, funded through the Indigenous Guardians Pilot program until 2022, created — among other activities — a composite range map that includes data and information on landscape and ecosystem health in the Pimachiowin Aki World Heritage Site (a 2.9 million ha boreal forest and Anishinaabe cultural landscape spanning the Manitoba-Ontario border); an information management system to incorporate storage, organization, and retrieval of information from a variety of sources over 40 years; and meetings with provincial governments to help align Guardian and government actions on monitoring efforts, timing, and information sharing (PAWHS, 2020).

6.2.2 Indigenous Land Management Practices

Traditional Indigenous management of natural resources in Canada is ancient in its origins and distinct from more recent European practices. Chief Robert Wavey of the Fox Lake Cree Nation in Manitoba writes:

> *I have often been asked for some positive examples of First Nations management of natural resources. The question implies that First Nations management is something that is either new or developing through agreements with governments. First Nations in Canada have never surrendered the role of managing the natural resources protected by Aboriginal rights. In fact, the use of resources by Aboriginal people and the stewardship of resources have always been tied together. Many specific sites have been continuously used by our communities for generations, indicating the success of the existing direct management and continued stewardship by the communities.*
>
> Wavey (1991)

Indigenous practices to manage, govern, and use land are diverse across Canada. These practices use Indigenous knowledge to inform decision-making and are often rooted in Indigenous views of plants, which consider reciprocity between humans and plants as a core element. This approach, in turn, leads to plant resource management systems and strategies (e.g., monitoring and identification of risk) that consider social and ecological values alongside economic values, and how plant health connects to the overall health of communities and ecosystems. In a 2019 assessment by 150 experts from around the world, analyzing 15,000 scientific publications as well as Indigenous and local knowledge, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that ecological spaces under the direct control or management of Indigenous communities have experienced slower declines in biodiversity through time in comparison to others (IPBES, 2019a). Similar global findings were identified in a 2020 study by the Rights and Resources Initiative, which found that Indigenous Peoples effectively conserve forests, ecosystems, and biodiversity through group ownership, Indigenous knowledge, and governance methodologies (RRI, 2020). The use of Indigenous knowledge presents opportunities to respect and adopt Indigenous principles and practices of land management, as well as the co-management of lands and resources between Indigenous communities and other actors (Turner *et al.*, 2020) (Box 6.2).

Box 6.2 The Anicinape People and the Reforestation of the White Pine

The Anicinape People of Kitcisakik, Quebec have taken the lead in calling for a collaborative approach to reforestation and new systems of sustainable management in an effort to create a forestry model that takes their own community needs into account and that restores the white pine on their traditional ancestral lands (Uprety *et al.*, 2017; Mulrennan & Bussieres, 2020). White pine is a culturally important keystone species to the Anicinape community. It is a source of medicine, timber, cultural sites, and landmarks, while also providing wildlife habitat, aesthetic value, and supporting biodiversity (Uprety *et al.*, 2017).

Over centuries, the number of white pine has decreased significantly for a variety of reasons that include pests, overharvesting, and fire suppression. In recent years, consultation on forestry operations has included Anicinape people, since their traditional lands reside on what is now public land managed by the provincial government and licensed forestry companies. In collaboration with academics and industry, Anicinape experts have created a plan for Indigenous stewardship that takes into account their community needs and creates the space for a working relationship in which Indigenous people are not just another actor, but a shared decision-maker (Uprety *et al.*, 2017).

Management strategies can incorporate both Indigenous and western knowledge[13]

Partnerships between Indigenous and non-Indigenous actors can help support the management of lands of all kinds, including forests, farms, and natural ecosystems (IPBES, 2019a). While Indigenous and other scientific methods are each valuable on their own, when combined, they can potentially provide a more fulsome picture or plan of action (Clayoquot Sound Scientific Panel, 1995; Uprety *et al.*, 2012). For example, scientists at Simon Fraser University searched 1,000

13 The term 'western knowledge' in this chapter refers to the knowledge system historically "guided by empirical measurements and abstract principles that help order the measured observations to facilitate the testing of hypotheses" (Agrawal, 1995), often facilitated by the scientific method. The Panel uses this term in line with research cited in this chapter, recognizing that these knowledge traditions are not exclusive to western systems, and that not all aspects of the biophysical world can be measured or tested.

published studies to collect the stories of over 90,000 people from 137 countries whose traditional ways of life depend on nature (Savo *et al.*, 2016). The stories were used to complement climate change science, including numerical data and computer models. Researchers found that the experiences and knowledge shared by farmers, Indigenous Peoples, and other actors with an intimate knowledge of their local environments — passed down through generations — provided a more focused lens through which to study and understand climate change; it was also a means of learning how people across the globe are either losing or adapting their traditional ways of farming, hunting, gathering, and their cultural practices (Savo *et al.*, 2016).

Another example of knowledge sharing between Indigenous and non-Indigenous experts is provided by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) — an independent advisory panel to the Government of Canada that assesses the status of species at risk of extinction; COSEWIC includes *Aboriginal traditional knowledge* (ATK) in its assessment process for each wildlife species assessment (COSEWIC, 2019). Further, the federal government has explicitly recognized incorporating Indigenous knowledge into some decision-making processes; the *Impact Assessment Act* (GC, 2019d) mandates that both western science and Indigenous knowledge can be used in decision-making processes relating to environmental impact assessments. The Panel notes, however, that knowledge sharing is complex, and needs to be done in a respectful and culturally appropriate way so that everyone involved benefits from the interaction (Box 6.3).

Box 6.3 Knowledge Sharing Through Two-Eyed Seeing and the Creation of an Ethical Space

Two-eyed seeing, a term and concept created by Mi'kmaq Elder Albert Marshall, focuses on the gift of multiple perspectives and engages diverse knowledge-holders without necessarily integrating knowledge systems (Buck, 2019; Bannister, 2020). Learning, in this sense, sees "from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of Western knowledges and ways of knowing, and to using both these eyes together, for the benefit of all" (Bartlett *et al.*, 2012). In this way, two-eyed seeing further enables the recognition of Indigenous knowledge as a whole knowledge system, side by side with western scientific knowledge. Under this approach, both perspectives are examined simultaneously and collaboratively when considering questions of science (Buck, 2019).

(Continues)

(Continued)

Cree philosopher and educator Willie Ermine put forward the idea of *ethical space,* where previously isolated cultures can meet:

> *The 'ethical space' is formed when two societies, with disparate worldviews, are poised to engage with each other. It is the thought about diverse societies and the space in between them that contributes to the development of a framework for dialogue between human communities. The ethical space of engagement proposes a framework as a way of examining the diversity and positioning of Indigenous peoples and Western society in the pursuit of a relevant discussion on Indigenous legal issues and particularly to the fragile intersection of Indigenous law and Canadian legal systems.*
>
> Ermine (2007)

Ethical space was emphasized as an essential concept by the National Advisory Panel in its report on Canada's conservation vision — specifically, the importance of actively working to create an ethical space of engagement across all parts of biodiversity conservation (NAP, 2018). This type of space is particularly important for the integration of Indigenous and western knowledge systems (NAP, 2018). The importance of ethical space was also raised in the *Indigenous Circle of Experts Report on Indigenous-Led Conservation*, which recommends creating Indigenous Protected and Conserved Areas (IPCAs) (ICE, 2018), as well as by the Indigenous Heritage Circle in its recommendations to Parks Canada regarding engagement with Indigenous Peoples (IHC, 2019).

While the Panel notes that the concepts of two-eyed seeing and ethical space may be challenging for regulators and various orders of government to incorporate, they nonetheless provide guiding principles for engaging with Indigenous Peoples and including Indigenous knowledge in a culturally appropriate and collaborative manner. This is in line with more recent discussions with Ermine who suggested moving forward from thinking of ethical space as a noun and, instead, thinking of it as a process (Ermine as cited in Bannister, 2020).

Indigenous management approaches consider multiple ecosystem functions

Indigenous management approaches often consider multiple uses for a given area of land. This type of decision-making can be seen in community forestry, an evolving branch of the forestry sector. Community forestry uses a management approach that supports multiple ecosystem functions, which aligns with an Indigenous land management ethic (Devisscher *et al.*, 2021). In community forestry, local communities have a prominent role in forest management and land-use decision-making (Teitelbaum, 2015). It operates on the principles of participatory governance, rights, local benefits, ecological stewardship, and multifunctionality (Palmer *et al.*, 2015; Devisscher *et al.*, 2021).

Community forestry in Canada is at the periphery of policy development, with most forestry land held by provincial and territorial governments and allocated to corporate actors via large industrial licences (Teitelbaum, 2015). But both Indigenous and non-Indigenous actors have identified community forestry initiatives as important alternatives in the forestry sector because of their potential to include development that is more adapted to local conditions and goals (Teitelbaum, 2015). For example, in northern Ontario, more resilient forms of forest tenure have been proposed through community forestry (Palmer *et al.*, 2015). Regional community forestry partnerships have started to form between First Nations and municipalities, and the forestry industry is increasingly supportive of these approaches (Palmer *et al.*, 2015).

The Xaxli'p Community Forest in British Columbia uses ecosystem-based planning to inform decision-making (XCFC, 2018a). This type of planning ensures "the protection, maintenance, and restoration of biological diversity, at all spatial and temporal scales," recognizing an important relationship among ecosystems, cultures, and economies (XCFC, 2018a). The community forest is managed to "restore degraded ecosystems and to create a sustainable community economy based on high quality timber and non-timber forest products" using ecosystem-based planning, with the goal of ecological and cultural sustainability (XCFC, 2018b). It was formalized in 2011, when Xaxli'p control over land use and management was recognized by the Government of British Columbia, before which time the territory was used for industrial forestry (XCFC, 2018c).

While these community forestry examples may appear isolated, and as having only localized impact, some have posited that, taken together, they can be seen to be influencing the direction of provincial forest-tenure policy (Palmer *et al.*, 2015). Moreover, these examples of community forestry have been supported by tenure reforms in several provinces. British Columbia introduced *Community Forest Agreements* in 1998 and in 2021 there are close to 60 community forests in that province (BCMFR, 1999; BCCFA, 2021). In Ontario, tenure reform encouraged the inclusion of more local and Indigenous communities in forest management agreements, and there are now several forest licences that are held by Indigenous communities (Gov. of ON, 2020c). The Canadian forestry sector therefore has expressed an interest, as yet unrealized, in moving away from solely timber-based forestry, illustrated through the emergence of a pan-Canadian bio-pathway[14] strategy, *The Bio-pathways Project* (NRCan, 2020i). With this and other projects focused on transitioning the forestry sector to the bioeconomy[15] still in their infancy, it is unclear how such changes will impact forestry land use. However, given the importance of environmental and ecological impacts in these pathways, the Panel notes that this shift should provide management opportunities for multiple ecosystem functions.

More broadly, the agricultural and forestry practices of Indigenous Peoples "often integrate economic, environmental, social and cultural considerations" (FAO, 2010). Mobilizing Indigenous expertise in plant system management is an important asset for addressing the challenges facing plant health today and in the future (FAO, 2010). For example, Indigenous forest gardens in British Columbia were managed ecosystems characterized by fruit, nut, and shrub species distinct from the conifer forests surrounding these sites (Armstrong *et al.*, 2021). Over 150 years after colonial-settler occupation displaced the Indigenous communities that tended these gardens, the gardens persist as distinct from the surrounding forest, with significantly higher species richness — including important food species planted outside of their native range, such as hazelnut (*Corylus cornuta*) and Pacific crabapple (*Malus fusca*) — as well as functional evenness and divergence (Armstrong *et al.*, 2021). Functional evenness and divergence reflect the abundance of each species filling a niche space, and the diversity in ecosystem functions among those species (Mason *et al.*, 2005). These traits contribute to ecosystem resilience, and likely help explain the persistence of forest gardens in the face of succession from encroaching conifer forests (Armstrong *et al.*, 2021).

First Nations and Métis people are a growing sector of the agricultural population

Indigenous people are often not included in the mainstream agricultural narrative in the Prairies (Arcand *et al.*, 2020). Yet they are connected to agriculture through pre-colonial trade networks (Boyd & Surette, 2010), agricultural provisions in the numbered treaties (CIRNAC, 2020), and through Indigenous-led farming and agricultural leasing on First Nations reserve lands (Arcand *et al.*, 2020). In the context of agriculture, Indigenous people have valuable knowledge and skills to contribute to the management of plant health. Many Indigenous agricultural practices demonstrate adaptability and resilience through time. For example, the Three Sisters intercropping system of corn, bean (*Phaseolus* sp.), and squash (*Cucurbita* sp.) — practised by Indigenous people across the Americas for

14 A bio-pathway is "a network of interconnecting technologies along which the forest industry evolves" (NRCan, 2020).

15 The bioeconomy "comprises those parts of the economy that use renewable biological resources from land and sea [...] to produce food, materials and energy" (EC, 2019).

generations — increases overall protein yield among the three crops compared to growing each alone (Mt. Pleasant, 2016).

In the Prairies, agriculture was a mechanism used by the Government of Canada to assimilate First Nations people (Tang, 2003). In the early 1880s, First Nations farmers on the Prairies were competitive in the agricultural economy, adapting new, dry-land farming techniques, planting new test crops, and successfully adopting a collective, agrarian lifestyle, as exemplified by the File Hills Farm Colony on the Peepeekisis Reserve. However, policies enacted by the federal government effectively sabotaged the future successes of First Nations farming in order to protect non-Indigenous farmers against competition (Tang, 2003). The *Indian Act* (1876) and its amendments prohibited First Nations homesteading and illegally implemented a permit system that restricted the sale of First Nations agricultural products (Daschuk, 2015).

Despite these decades-long barriers, First Nations people continue to participate in the agricultural sector in Canada, as farmers, landlords negotiating lease agreements with non-Indigenous farmers, and as agri-business entrepreneurs (Arcand *et al.*, 2020). For example, the *Treaty Land Entitlement Framework Agreement*, signed between First Nations and the federal and Saskatchewan governments in 1992, enabled 25 First Nations to acquire up to nearly one million ha to address land shortages originally promised in Treaties 4 and 6 (CIRNAC, 2015). One ongoing challenge is the limited number of First Nations farmers with first-hand knowledge of farm operations (Arcand *et al.*, 2020). In a forum on revitalizing Indigenous agriculture that included 62 Indigenous people from 24 First Nations across Saskatchewan, Arcand *et al.* (2020) found an increasing interest in food sovereignty and land-use plans that emphasize ecosystem health and sustainability. There are also calls to create sovereign agricultural economies that support community-defined economic and cultural goals, including a revitalization of traditional food cultivation practices using traditional relationships to the land. While many people recognize that reserve lands are likely to continue supporting large-scale commercial agriculture as a revenue source, there is also a desire for policy change and capacity building to grant greater Indigenous control over "economic, social, cultural, and environmental outcomes of agricultural activities" (Arcand *et al.*, 2020).

Self-identified Indigenous people made up approximately 3% of the agricultural population in Canada in 2016, representing 15,765 individuals — an increase of 21% when compared to 1996, during the same time the total agricultural population fell by 39% (Gauthier & White, 2019). Métis people make up the largest proportion of the Indigenous agricultural population (70%), followed by First Nations people (26%), Inuit (1%), and those who identify with multiple Indigenous identities or identities not included in the survey (3%) (Gauthier & White, 2019).

Conversely, in 2020, 7% of the forestry sector workforce identified as Indigenous (NRCan, 2020k), relative to the total workforce in Canada, which is 4% Indigenous (StatCan, 2021b).

6.3 Impacts of Poor Plant Health on Indigenous Communities

Globally, Indigenous Peoples are disproportionately affected by environmental degradation and development activities that negatively impact ecosystems, as well as Indigenous livelihoods, cultures, and nutrition (FAO, 2010). Not only are the impacts inequitably distributed, but Indigenous people have also not been part of the decision-making processes that brought about these harms.

The loss of plant habitat has unique detrimental consequences for Indigenous Peoples

Land-use change (e.g., logging, oil extraction, mining), in combination with climate change and the introduction of invasive species, has contributed to the degradation of ecosystems and exacerbated the loss of Indigenous people's access to traditional plant-harvesting areas and foods in Canada (Turner, 2020). These changes pose notable food security risks for Indigenous communities. Climate change has already contributed to a reduction in the availability and quality of traditional foods, and the ability to hunt and harvest among Inuit communities in the North; this, in turn, has reduced their diet quality (Beaumier & Ford, 2010; Wesche & Chan, 2010). Although most of the affected traditional foods are animal species, multiple berries of nutritional importance (e.g., cloudberry, *Rubus chamaemorus*) have also been affected (Wesche & Chan, 2010). Indigenous people report that berries are increasingly more difficult to find, are of declining quality, rot more quickly, and are more prone to insect damage (Downing & Cuerrier, 2011). For example, huckleberry (*Vaccinium membranaceum*) is a nutritiously and culturally important plant species for First Nations in British Columbia (Trusler & Johnson, 2008). Recent modelling shows that huckleberry habitat will decrease across most of its current range, and fruiting will begin over a month earlier, affecting the location and timing of traditional harvesting (Prevéy *et al.*, 2020). For Indigenous communities, the use of plants for food, materials, and medicine is foundational to cultural identity, so climate-induced changes to the distribution of plant species will also result in cultural losses (Downing & Cuerrier, 2011).

The increasing use of traditionally foraged plants puts them at risk of overharvesting

Herbal medicine is growing in popularity in Canada, with many therapeutic herbs primarily gathered from natural habitats (Westfall & Glickman, 2004).

Consequently, some populations of plants used by Indigenous Peoples are at risk of overharvesting. A formal system of accounting for foraging does not exist, so there is little information about which plants are harvested, from where, and in what quantities (Westfall & Glickman, 2004). Policies and regulations could protect these important plants from overharvesting by non-Indigenous people, and Westfall and Glickman (2004) propose monitoring systems as part of the solution. Recognizing Indigenous laws and management practices could also play a role in reducing threats from overharvesting. For example, Gwich'in women in the Northwest Territories direct the allocation of berries (an important food resource) through the interpretation and application of Gwich'in resource law (Napoleon & Overstall, 2007). Berry-harvesting activities are regulated through the control of access, information, and the sharing of the harvest, which depend on factors such as the scarcity or abundance of berries, environmental conditions, as well as social responsibilities and kinship relationships (Napoleon & Overstall, 2007).

6.4 Indigenous Engagement in the Plant Health System

While Indigenous communities, rights-holders, and experts have been long omitted by policymakers in Canada, the need for the inclusion of Indigenous representation — that goes beyond mere consultation — is now not only well known, but a legal requirement (Brideau, 2019; GC, 2019c). This relates specifically to plant health; as discussed in Sections 6.1 and 6.2, Indigenous Peoples not only have rights over the land where plants grow, but also unique knowledge and expertise about plants and how they have adapted through time.

Indigenous people play a crucial role in enhancing the Canadian plant health system

While Indigenous communities are noticeably absent from the CFIA's list of key partners (CFIA, 2017b), Indigenous knowledge has been recognized in more informal CFIA presentations as an important component of an enhanced plant health decision-making system (Bilodeau, 2020). Indigenous voices are critical in many areas of plant health based on their unique expertise, their management, governance, and land use across Canada, and the Crown's commitment to protect their constitutionally recognized rights. In some areas of government, there is increasing recognition of the important role Indigenous governance over land areas can play in conserving ecosystem health and biodiversity, while also allowing for traditional cultural activities (Box 6.4).

Box 6.4 Indigenous Protected and Conserved Areas

In 2017, the Indigenous Circle of Experts (ICE), a group of both Indigenous and non-Indigenous members, recommended that Parks Canada create Indigenous Protected and Conserved Areas (IPCAs), where Indigenous governments "have the primary role in protecting and conserving ecosystems through Indigenous laws, governance and knowledge systems" (ICE, 2018). IPCAs include lands, waterways, and tribal parks, and share three essential features: they are "Indigenous led," "represent a long-term commitment to conservation," and "elevate Indigenous rights and responsibilities" (ICE, 2018). In these areas, Indigenous governments have the principal role in "determining the objectives, boundaries, management plans and governance structures" (ICE, 2018).

IPCAs are more than places of conservation, which in the past, through the creation of protected parks, have limited Indigenous land use and have had profoundly detrimental impacts on Indigenous communities (Spalding, 2020). IPCAs are envisioned as spaces for cultural regeneration where communities can create sustainable livelihoods, teach, learn, and restore lands, waters, and cultural ways and traditions (Linnitt, 2018; Mulrennan & Bussieres, 2020). While there are no formally recognized IPCAs in Canada as of yet, there are several tribal parks. These include Dasiqox Tribal Park, K'ih tsaa?dze Tribal Park, and Tla-o-qui-aht Tribal Park, all located in British Columbia (David Suzuki Foundation, 2018). These parks have been described as "a model for land management in Canada that supports both ecosystem and human use of the land" (David Suzuki Foundation, 2018).

Indigenous-led NGOs, or ones that focus on issues of particular relevance to Indigenous people, can act as important intermediaries among Indigenous communities and federal, provincial, and territorial governments by providing resources to build local capacity and support, and by advocating for the incorporation of Indigenous knowledge in decision-making (CCA, 2019a). For example, the National Aboriginal Forestry Association (NAFA) promotes the practice of responsible forestry management and the involvement of Indigenous communities in the forestry sector. Through these practices, NAFA works toward the economic empowerment of Indigenous communities, while also protecting lands of cultural and spiritual significance through holistic traditional practices (NAFA, n.d.).

The CFS has recognized the intrinsic value of Indigenous knowledge and has been working on integrating a collaborative approach using co-creation of knowledge that combines western and Indigenous knowledge into its practices (NRCan, 2020k). One pan-Canadian surveillance example using these types of collaborative approaches is BudCam, which is a network monitoring the climate change effects on the timing of the first budburst on black spruce (*Picea mariana*). Black spruce is found throughout the boreal forest, and therefore a monitoring network must cover considerable geography. This presented opportunities for collaboration, and several First Nations are now participating in this network across the country (NRCan, 2020h). The goal is to exchange knowledge about the land, and also to create new knowledge together (NRCan, 2020k).

While Indigenous knowledge has been incorporated in some government strategies, as discussed above, it has not been used to inform plant health decision-making on a large scale. The inability to incorporate a more holistic management approach to plant health risks into the regulatory and decision-making framework represents a governance risk to plant health — not all available knowledge is being incorporated into policy.

7

Answering the Charge

Healthy plants are inherently valuable to people living in Canada and to Canadian ecosystems. Plants create value by provisioning, regulating, and supporting ecosystem functions, such as food and fibre production, climate and water regulation, and nutrient cycling. In turn, these functions provide economic, environmental, social, and cultural benefits. Plant life depends on different components of the environment, including soil, temperature, and water availability, as well as other organisms, such as pollinators and beneficial fungi. They provide food resources for other organisms — the vast majority of life on Earth, including humans, relies on plant primary production. Risks to plant health threaten Canada's economy, food production, forestry activities, and many other ecosystem functions (e.g., air quality, social well-being, carbon fixation) that plants provide. Plant health risks include the loss of Indigenous people's ability to access, manage, and care for the land in traditional ways important for the maintenance of livelihoods and cultures. Plant health also impacts, and is impacted by, the biodiversity and health of Canadian ecosystems and the everyday lives of people in Canada.

Recognizing the extent to which the economy, environment, and people in Canada rely on plants, the CFIA asked the CCA to convene an expert panel to assess the following charge and related sub-questions:

What are the most significant current and emerging risks[16] to plant health in Canada?

- What are the gaps in Canada's plant health system with respect to identifying and addressing current and emerging plant health risks?
- What promising and leading risk management practices, including indicators[17] and metrics,[18] could be used to improve the ability of Canada's plant health system to adapt and respond to current and emerging risks?

7.1 Current and Emerging Risks to Plant Health

Risks to plant health are multifaceted, interrelated, and complex. The Panel determined that identifying and prioritizing specific, individual risks to plant

16 Of specific interest are risks associated with climate change, movement of people and goods, adoption of new crops and cultivation practices, and changes in land-use practices.

17 Indicators include those used to inform thresholds for tolerance to plant health risks.

18 Metrics include those used to assess the effectiveness of prevention or mitigation measures.

health would be insufficient for capturing the full scope of the charge, given the diversity of plant life in Canada; the variety of management systems and actors both within and among agriculture, forestry, and natural ecosystems; the complexity of shared responsibilities among federal, provincial, territorial, municipal, and Indigenous governments; as well as the roles of NGOs, industry, academia, and private landowners — among others — in supporting plant health.

There are also diverse approaches to plant health risk management in Canada, which reflect the local context, the different prioritizations of values among actors, and the feasibility of different strategies for specific situations. Crop production, crop types, risk management strategies and objectives, and economic reliance on agriculture vary by region, as do forestry operations, management practices, and economic reliance on forestry and forest products. Cultural values, climate change impacts, and conservation priorities also differ across the country. For example, Indigenous worldviews represent an understanding of the relationships between plants and people that defines priorities and responsibilities in ways that can differ from commercial or western scientific approaches, but that can also differ among Indigenous communities across the geography of Canada. The potential severity of damage to plant health resulting from risks also varies among sectors and communities — as well as over time — and may look different for an individual farmer, logging company, or greenhouse operator; a provincial or territorial regulator; an Indigenous community; or a global trade organization. Thus, there is no consensus on the characterization, prioritization, or appropriateness of mitigation measures for individual plant health risks among diverse actors who hold differing and sometimes conflicting perspectives. At the same time, there are commonalities across perspectives when it comes to characterizing plants and plant ecosystems that are vulnerable to risks, as well as commonalities in strategies to support resilience.

With this in mind, the Panel identified ten plant health risk categories in three key areas (Table 7.1): (i) the environment, encompassing both biotic (living, e.g., pollinators) and abiotic (non-living, e.g., weather) elements that support plant functioning, and (ii) pests, which damage plant functioning and include predators, competitors, and pathogens. The Panel also noted the overarching role humans — including societies and institutions — play in plant health. Risks to plant health therefore include (iii) governance risks, such as risks to the operation and functioning of the plant health system itself, as well as risks to plant health created or exacerbated by the exclusion of, and damage to, Indigenous communities, practices, and knowledge. Notably, many risks span multiple ecosystem types (shaded boxes in Table 7.1), suggesting opportunities for engagement and coordination in addressing these risks.

Table 7.1 Ten Plant Health Risk Categories with Examples, Characterized by Risk and Ecosystem Type Primarily Affected

Risk Type	Risk Categories	Examples from the Report	Primary Ecosystem Type		
			Forestry	Agriculture	Natural Ecosystems
Environment	Climate Change	• Long-term temperature and precipitation shifts			
		• More frequent and severe extreme weather events			
	Loss of Soil Health	• Biological, physical, and chemical limitations (e.g., microbial functional diversity, hardness, salinity)			
	Loss of Pollination Services	• Decline in pollinator populations			
		• Phenological mismatches between plants and pollinators			
	Loss of Habitat	• Lack of dispersal and adaptive capacity of plant populations			
Pests	Pest Introduction and Spread	• Pest introductions via packing materials, containers, and soil			
		• Weed seed introductions via imported grain			
		• Horticulture and landscaping imports becoming pests			
		• Pest spread via road infrastructure, and domestic trade and travel			
		• Natural dispersal mechanisms (e.g., wind, water, animals)			
	Control of Pest Populations	• Loss of tools and strategies due to adaptation of pest populations			
		• Lack of resilience due to lack of temporal and spatial diversity			
Governance	Lack of Tools and Strategies	• Limited capacity to manage, analyze, and interpret big data			
		• Insufficient research and development of diverse tools and strategies			
		• Limited access to, and application of, tools and strategies for different contexts			
	Failures of Communication and Coordination	• Competing plant health paradigms and diversity of goals			
		• Duplication of effort or lack of clarity in the plant health system			
		• Lack of coordination and communication among relevant actors			
	Lack of Engagement and Trust	• Lack of public trust in the regulatory system			
		• Failure to effectively engage different publics			
	Exclusion of Indigenous People and Practices	• Loss of plant-related Indigenous knowledge and practices			
		• Access to lands and land-based learning limited or lost			
		• Failure to learn from and support Indigenous management practices			
		• Lack of inclusion in planning, decision-making, and implementation			

Exacerbating factors create an ongoing demand for research, resources, and innovation

Part of the challenge of identifying current and emerging risks to plant health lies in the complexity and uncertainty of predicting the likelihood and impact of specific risks for a given time or place. For example, a new pest species introduced through international trade may be limited in its range to areas close to a port facility and have an initially minor or largely unobserved impact on plant health in Canada. Over time, however, environmental conditions may become more suitable for pest population growth and expansion. Such changes could be driven by shifting land-use practices, the planting of a susceptible crop, unusually mild winter temperatures, or any number of other factors resulting from human actions, including climate change. Changes in plant-pest relationships may also be the result of adaptation by the pest population to new environmental conditions or host species, or a change in the susceptibility of plant populations to the pest due, for example, to a loss of genetic diversity. Without robust surveillance and monitoring, the distribution of the pest in Canada could expand substantially before impacts are detected, ultimately resulting in significant damage.

This generalized scenario reflects the challenge of characterizing and prioritizing any one risk to plant health due to the exacerbating factors of climate change, the movement of people and goods, and evolutionary processes, which can increase the frequency and rapidity of adverse events. Mitigating risk in such a dynamic landscape is not insurmountable, but requires consideration and investment in key strategic areas:

- Reducing the vulnerability of plant ecosystems to pest population establishment and growth.
- Improving detection and control of pest introductions through surveillance, monitoring, coordination, and communication.
- Mitigating the impacts of changes to the biotic and abiotic environment through strategies to improve the tools and resources available to manage adverse events.
- Improving the resilience of plant ecosystems that experience adverse events by enhancing biodiversity and functional redundancy.
- Adapting the governance of the plant health system to a dynamic and unpredictable risk landscape, using strategies to improve forecasting and scenario planning; fostering innovation; and including a diversity of knowledge systems, management practices, and perspectives.

A continuous risk management approach can be useful in addressing a dynamic risk landscape, allowing for an iterative and adaptive process that is centred on communication and documentation (recall Figure 2.2). Additionally, practices and strategies to reduce vulnerability (e.g., robust surveillance and monitoring for changes in pest populations) and to increase resilience (e.g., functional redundancy in plant ecosystems) can help reduce the likelihood and potential impacts of plant health risks.

There is a need for the assessment of appropriate and relevant indicators and metrics across all aspects of the plant health system

Indicators of plant health include measurements of ecosystem functions of interest, such as water quality or crop yield. Metrics may be quantitative, such as estimates of crop yields or timber production, the number of visitors to a nature area, estimates of species diversity or abundance, or the economic cost of invasive species control. However, plant health metrics may also be qualitative, such as the ability to support a sense of community, the well-being of farmers, or the opportunity to partake in traditional practices.

An essential part of an adaptive approach to risk management includes measurement of the effectiveness of management actions. However, such measurements differ across plant systems and ecosystem functions of interest, and few are consistently or repeatedly monitored over time and space. Moreover, technologies such as precision agriculture and DNA testing are rapidly increasing our ability to measure and detect a wide variety of biotic and abiotic factors. The interpretation of these data (including inferences drawn about the state of plant health from sensor data) and their accessibility to practitioners (so they may inform decision-making) are areas of active development. While this report includes indicators and metrics of plant health as examples, a fulsome consideration of these could warrant its own report, and, indeed, such exercises have been done in the past.[19] The development of new methodologies — including both technological and practical innovations as well as advances in statistical methods — coupled with the complexity and uncertainty introduced by exacerbating factors, offer an opportunity to review such exercises. The Panel also notes that the metrics chosen tend to drive the types of management strategies employed (i.e., “what you measure is what you manage”), suggesting that a careful and deliberate consideration of plant health indicators and metrics is warranted to inform future policy decisions.

19 See, for example, the Canadian Council of Forest Ministers’ 1997 technical report, *Criteria and Indicators of Sustainable Forest Management in Canada.*

7.2 Gaps in the Plant Health System

Canada's diversity — in plant ecosystems, geography, values, objectives, and perspectives — is a strength. Diverse actors in Canada have mandates to protect plant health, develop priorities, and implement strategies to address risks specific to their regions and interests. However, different priorities and the distribution of responsibility among diverse actors can also result in gaps in the implementation and evaluation of management actions to prevent, mitigate, and adapt to plant health risks.

A lack of communication can create gaps in surveillance and mitigation efforts, as well as missed opportunities to collaborate

As part of a global trading system, Canada (like all countries) balances international obligations with domestic economic interests, public safety, and ecological protection. Communication and coordination are particularly relevant to the plant health system for overarching issues such as climate change. Strong collaboration and communication — as well as networks that connect academia, governments, NGOs, and industry with other actors (including members of the public) — are essential for the plant health system to successfully deploy available resources and knowledge. Among the most significant risks to a robust and responsive plant health system are the information silos produced by different actors. Failures of communication and coordination occur when relevant expertise, knowledge, and evidence are not shared among groups, or when federal, provincial, or territorial departments or agencies, or other key actors, are omitted entirely from regulatory and decision-making processes.

Coordination can also be challenged by shifting political priorities — as governments change with election cycles, agencies may struggle with maintaining consistent approaches. Thus, there is an opportunity for a shared vision (and standard operating procedures) across relevant agencies and jurisdictions to coordinate and facilitate actions that prioritize surveillance, planning, response, and evaluation in plant health risk management. Robust evaluative practices include scenario testing (i.e., examining risk outcomes and interactions over long time periods) and sensitivity testing (i.e., examining immediate responses to short-term shocks), which can assess the functioning and responsiveness of the plant health system prior to the occurrence of an adverse event.

Loss of Indigenous knowledge, and its lack of inclusion in decision-making, is a risk to plant health and an infringement of Indigenous rights

There is a deep and longstanding relationship between Indigenous Peoples and plant life. Indigenous plant health management is rooted in history and integral to contemporary life. Indigenous Peoples across Canada have responded and adapted to environmental changes for millennia, and their expertise can be especially valuable in understanding changes through time. Moreover, First Nations, Inuit, and Métis Peoples are prominent rights-holders in Canada. Land rights require that federal, provincial, and territorial governments carry out consultations and (potentially) accommodations, if Indigenous and treaty rights may be infringed on by proposed policies or developments. Policies rooted in colonial legacies, as well as some resource extraction projects, threaten Indigenous knowledge and legal traditions related to plant health, including Indigenous agricultural practices and forestry management. Lack of awareness or loss of existing knowledge is a risk to plant health, as are barriers to the development of new knowledge. While Indigenous communities, rights-holders, and experts have been long omitted by policymakers in the governance of plant health, the need for the inclusion of Indigenous representation — that goes beyond consultation — is now well known. This inclusion is also an opportunity for Canada to meet its legal obligations while mitigating economic, social, cultural, and environmental impacts due to plant health risks, and move towards reconciliation.

7.3 Promising Practices in Plant Health Risk Management

There are a multitude of practices for managing risks to plant health. The applicability of any one practice will depend on different factors, including the local context, specific goals, and lead actors responsible for the implementation of the management strategy. For example, while the development of drought-tolerant crop varieties may be a promising practice for areas predicted to experience increased frequency and severity of droughts, it will be less of a priority for areas predicted to experience greater precipitation or increased pest problems. Some management practices may also be promising when used in combination with others; for instance, clubroot-resistant varieties of canola are being registered for use, but a minimum length of crop rotation remains a leading practice to both reduce the severity of clubroot outbreaks as well as maintain the durability of resistance in these varieties. As with indicators and metrics, a detailed assessment and ranking of promising practices could warrant its own report. Therefore, the Panel has more broadly categorized areas of promising practices by the type of risk they primarily address (i.e., environment, pest, governance), as well as their target areas of action with respect to risk management (i.e., prevention, mitigation, or adaptation — shaded boxes in Table 7.2).

Table 7.2 Areas of Promising Practices for Addressing Different Types of Risks to Plant Health, Categorized by Targeted Areas of Action for Risk Management

Risk Type Addressed	Area of Promising Practice Exemplified in the Report	Target Areas of Action		
		Prevention	Mitigation	Adaptation
Environment	• Breeding for stress tolerance			
	• Efficient water management			
	• More efficient use of inputs			
	• Soil conservation practices			
	• Sustainable management practices			
	• Assisted migration of plants			
	• Increasing protected land			
Environment and Pests	• Precision agriculture and forestry			
	• Increasing diversity and functional redundancy			
	• Molecular and digital surveillance and monitoring			
Pests	• Integrated pest management			
	• Diversification of crop and forestry species			
	• Novel crop protection products and modes of action			
Governance	• Increasing capacity and skills with new technologies			
	• Diversification of management practices and goals			
	• Enhancing coordination and transparency with plant health research, management, and regulation			
	• International standards for phytosanitary measures			
	• Early engagement with different publics			
	• Active engagement with, and inclusion of, practitioner knowledge			
	• Public and Indigenous-led plant monitoring initiatives			
	• Active encouragement and respectful inclusion of Indigenous knowledge			
	• Recognition of and support for Indigenous management practices			

Practices that target risk prevention include surveillance and monitoring for plant health risks, such as surveillance for new pests or monitoring pest population growth; these can be coupled with actions that prevent these risks from manifesting, such as phytosanitary procedures (to destroy pests prior to introduction) or eradication efforts (post-introduction). Mitigation practices are applicable when prevention is not feasible, but actions can be taken to reduce the frequency of occurrence or severity of impact. For example, the implementation of an integrated pest management strategy to mitigate an anticipated pest outbreak might include targeted monitoring, planting a resistant variety of crop, and specially timed pesticide applications to minimize pest damage to a crop. Adaptation practices do not target the risk itself, but rather seek to limit the impact of a risk by bolstering the ability of a plant (or plant ecosystem) to continue or recover function when an adverse event occurs. This might include breeding crops for stress tolerance, the assisted migration of plants, and management practices to increase functional diversity and redundancy in plant ecosystems.

Some risks are systemic — that is, they are embedded in a broader social and institutional context and cannot be evaluated adequately without considering interdependencies and ripple or spillover effects on seemingly unrelated systems. Promising practices may also be applied to the functioning of the plant health governance system itself, addressing gaps and inefficiencies.

Risk governance approaches inclusive of diverse experiences and knowledge can help to identify, assess, and manage complex plant health risks

Governance is a term that reflects the multitude of actors and processes that lead to collectively binding decisions; this includes government institutions, but also economic forces and civil society actors. Risk governance approaches rely on communication and deliberation to meaningfully engage with diverse perspectives; such approaches must be cautious and flexible to enable learning. The experiences and knowledge shared by farmers, Indigenous experts, foresters, and others who understand their local environments can provide a focused lens through which to study and understand the complex interactions among plants, pests, and the environment. For example, Indigenous communities in Canada have management and cultivation practices distinct from European traditions that can support the management of plant health. Building relationships with Indigenous communities presents opportunities for the respect and adoption of Indigenous legal traditions and principles of land management, as well as co-management (between Indigenous communities and other actors) of lands and resources. A multidisciplinary, cross-sectoral approach can help ensure that knowledge existing in other disciplines or communities is not excluded by the framing of a given risk question.

Building expertise among practitioners and regulators on the effective use and management of data supports a robust, forward-looking plant health system

The influx of data being produced by new technologies in agriculture and forestry promises to bolster the development of precise and responsive risk management strategies; these data will be of little relevance, however, unless they can be managed, accessed, and interpreted accurately. While there is ongoing research and development in agriculture, forestry, and conservation, it is not clear whether Canada's current education and training programs are adequate to fully take advantage of these innovations. In particular, the increasing volume and rapidity of data acquisition point to a need for specialists in data management and analysis. Almost all areas of research are facing similar deluges of big data, and there is a risk that such transferable expertise may impede agriculture and forestry's access to highly qualified personnel. As well, with more information comes a greater need for knowledge translation and decision-making supports. These will need to be available and accessible to farmers, foresters, and landowners who may not possess specialized skills in interpreting data. The cost of adopting digital technologies in forestry and agriculture is also an important barrier that can exacerbate inequality and reduce the effectiveness and lengthen the adoption time of new technologies. A robust plant health system is one that implements tools and practices that improve the detection and understanding of threats to plant health, and facilitates the accurate interpretation and use of plant health data. Such an influx of plant health data can also be used to inform forward-looking activities, such as scenario planning, whose relevance depends on an accurate representation of the plant health system to best support realistic scenarios, actions, and consequences.

Biodiversity and redundancy in ecosystem functions are the main mechanisms for building and maintaining resilient plant ecosystems

Practices that can improve ecosystem resilience include supporting biodiversity and redundancy of ecosystem function in agriculture, forestry, and natural ecosystems. For example, crop rotation is a widely used technique that adds temporal diversity in plant species to agroecosystems, which can increase yield stability, reduce the incidence and impacts of some pests, and protect soil health. In forestry, the application of techniques to measure functional diversity and complex spatial networks can help direct stewardship actions to strengthen a forest's natural adaptive ability, productivity, and resilience in the face of global change. At a governance level, mobilizing and coordinating citizen scientists, municipalities, and community programs can allow for a widespread and robust monitoring and surveillance network that would otherwise be beyond the resource capacity available to any one government agency.

Supporting a diversity of plant protection tools, as well as surveillance and management practices, requires a regulatory framework that facilitates research, development, and adoption of new technologies

While the Canadian regulatory system is well respected, science-based, and considerate of safety standards, inefficiencies in the assessment and authorization timelines for innovations in feeds, seeds, fertilizers, and plants with novel traits have also been noted. The challenge of creating an effective regulatory system for pesticides, for example, is one of balancing timely access to new tools and products in a way that allows producers to manage plant health risks with the continued protection of public safety and the environment. The availability of different tools and strategies alone is not sufficient to manage plant health risks, as decisions must be made by practitioners regarding their appropriate and timely use, which, in turn, depends on factors such as local soils, weather forecasts, skills and education, equipment availability, and costs, among others. As well, the effectiveness of tools and strategies is expected to differ geographically and change over time. Ongoing monitoring, research, and development, as well as responsive and timely regulatory processes, are therefore necessary to ensure risk management tools and strategies can be successfully made available to, and implemented across, a diversity of practitioners and ecosystem types.

A key component of a robust plant health system is good risk communication

Without adequate communication, decisions can appear arbitrary, evidence can seem unstable, and the trust and support of actors and the public can be lost. Public engagement is important in assessing plant health risks and in creating effective policies. This engagement is meaningful if it allows time for true participation and deliberation, acknowledges members of the public as knowledge-holders, and builds listening into the communication process. People are more inclined to trust engagement efforts when they feel their input is valued and used in decision-making. There is room for improvement in efficiency, consistency, and transparency in the governance of plant health in Canada, in order to support growth and innovation in different areas, including the regulation of new products. Failure to appropriately communicate uncertainties can lead to misrepresentations of risk — wasting time, effort, and funding, and losing public trust and concern.

Implementation of practices to increase diversity and functional redundancy relies on governance, financial, and community supports

Diversifying ecosystem services in managed agricultural and forestry systems — and increasing functional diversity and redundancy — increases resilience in the face of adverse events. However, increases in resilience over the long term are generally traded off against higher potential economic returns from any one service in the short term. Some farming practices that favour the maintenance of functionally diverse plant ecosystems may only be profitable if products are sold at a premium, which may not be economically feasible for commodities produced for export to the global market. Other practices, such as payment systems for ecological goods and services, have been proposed, but are not yet implemented in Canada. Similarly, most forest management in Canada operates in a system built to optimize timber production to maximize financial returns, and it may be a substantial challenge to meaningfully change this status quo. However, by providing more than one good or service from a given area of land — for example, not just timber but also wood-based bio-energy, climate change mitigation, water or carbon storage, recreational activities, and non-timber forest products — forests and agricultural systems can be multifunctional, offering both economic and non-economic benefits. The implementation of diverse management practices, whether they include new technologies or the application of established practices in new contexts, relies on financial and community supports to manage the economic risks of adoption and to facilitate learning. While managing plants for multiple ecosystem functions may pose a substantial economic risk for producers in the short term, the Panel considers it a preferable long-term strategy for addressing plant health risks — one that may be mitigated by policy levers, subsidies, and community supports.

7.4 Panel Reflections

Risks to plant health are multifaceted, interrelated, rapidly evolving, and complex. The government agencies and actors charged with protecting plant health in Canada operate within a global framework that values efficiency and productivity and that tends to prioritize the economic value of plants. From this perspective, plants are primarily managed for economic returns, which provide employment opportunities for many people living in Canada. However, the Panel wishes to underscore that there are many ways to define and thus approach and manage plant health, which coincide with a growing understanding of the ecological functions of plants. Considering other ecosystem services — such as social and environmental values — alongside production values results in different frameworks for understanding risk, and different approaches to protecting plant health. Such approaches may not only consider abiotic and biotic threats to plant health, but also how social, economic, and cultural forces within current production systems contribute to plant health risks or further exacerbate them.

Broadening perspectives depends on a transdisciplinary approach that includes the natural and social sciences as well as Indigenous knowledge systems and practical expertise; it focuses on the management of plant health risks with an understanding of how risks are intertwined with ecological, cultural, or organizational issues. The scope of the challenge of protecting plant health in Canada is unprecedented, as will be the solutions required to address them. Plants are foundational to the economic, cultural, physical, and spiritual well-being of people in Canada. Though many people may be unaware of the role plants play in their everyday lives, the ecological functions plants provide support the basis for most life on Earth. However unprecedented a task, rising to the complex challenge of addressing current and emerging risks to plant health is an achievable and urgent imperative for ensuring our collective future.

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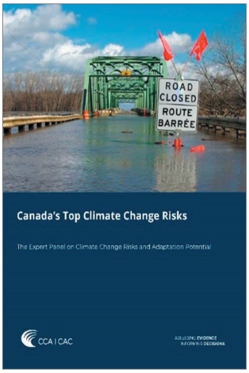
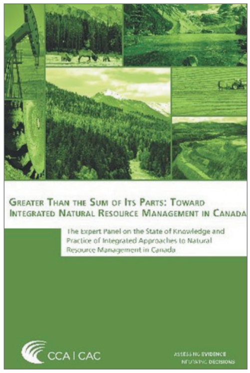
CCA Reports of Interest

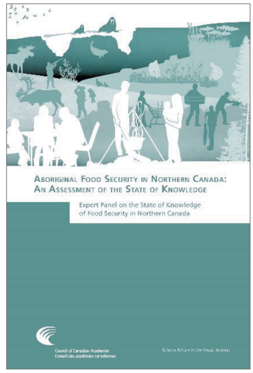
The assessment reports listed below are available on the CCA's website (www.cca-reports.ca):



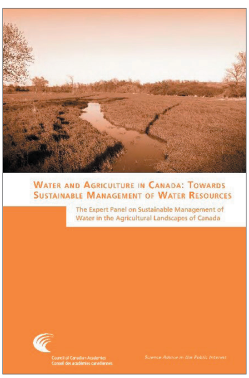
Canada's Top Climate Change Risks (2019)



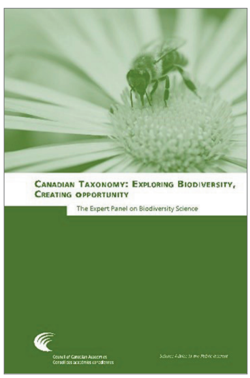
Greater than the Sum of its Parts: Toward Integrated Natural Resource Management in Canada (2019)



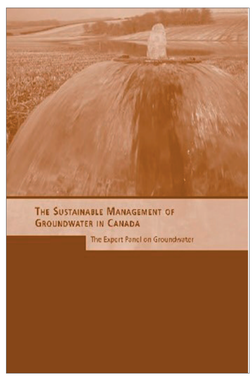
Aboriginal Food Security in Northern Canada: An Assessment of the State of Knowledge (2014)



Water and Agriculture in Canada: Towards Sustainable Management of Water Resources (2013)



Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity (2010)



The Sustainable Management of Groundwater in Canada (2009)

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*As of January 2022

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